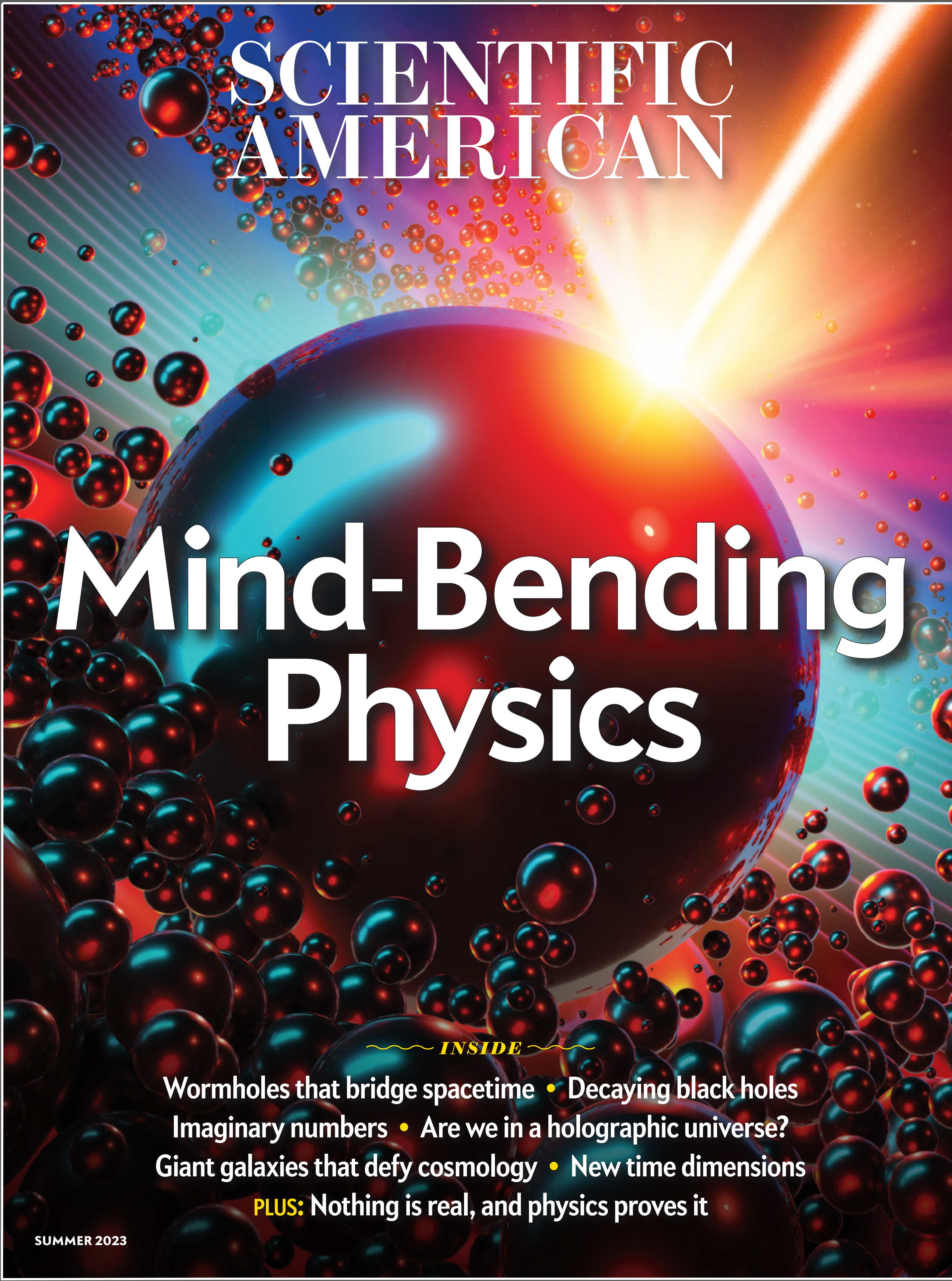
SPECIAL COLLECTOR'S EDITION



SCIENTIFIC AMERICAN

Mind-Bending Physics

INSIDE

Wormholes that bridge spacetime • Decaying black holes
Imaginary numbers • Are we in a holographic universe?
Giant galaxies that defy cosmology • New time dimensions
PLUS: Nothing is real, and physics proves it

SUMMER 2023

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FROM THE EDITOR

Perpetual Puzzle

Scientific American recently asked a variety of physicists: What is the most surprising discovery in your field? Some common themes included the expansion of the universe, neutrinos and their oscillations, and black holes. Particularly surprising was dark energy. "None of us working in physics saw that coming!" said Katherine Freese, theoretical astrophysicist at the University of Texas at Austin, about the unidentified force that makes up most of the universe. Physics is full of such mind-bending discoveries, many of which have only just been made.

> For every puzzle in physics, there is a team looking for an answer, which in turn cracks open a nesting doll of additional puzzles.

Take our baffling universe. Recent data from the James Webb Space Telescope reveal giant galaxies that formed only a few hundred million years after the big bang, conflicting with the generally accepted time line of cosmic events (*page 4*). Those who work on the so-called expansion problem in physics (two measurements of the universe that don't agree) eagerly await further data from JWST and several other important telescopes coming online this decade (*page 14*). An upcoming experiment housed deep underground in a Sardinian mine is designed to determine the weight of empty space—yes, it weighs something—and could help solve some of these conundrums (*page 30*).

In other laboratories on Earth, researchers have designed materials that manipulate light waves to make cloaking devices and other cool tech (*page 42*), and materials simulated with light waves are revealing inexplicable physics (*page 70*). Some exotic materials change states of matter regularly over time much like atomic crystal structures repeat in space (*page 58*), and scientists recently transformed the matter phase of a substance and simultaneously opened a new dimension in time (*page 66*).

Nothing alters spacetime more than black holes, which may connect through wormholes to *other* black holes (*page 80*). The black hole boundary, called the event horizon, is where all light is swallowed up, and studying it might explain what is beyond the observable edge of the universe (*page 88*).

The physics of the event horizon is a long-standing problem in quantum mechanics. Researchers have announced they have a way to study what happens to matter falling into a black hole by harnessing the elusive glow of space particles during rapid acceleration (*page 99*). Electrons are crucial to quantum experiments, though fundamentally perplexing: they have spin, which gives them quantum properties, but they themselves can't spin (*page 102*). So where does their spin come from? Such brainteasers are common in quantum physics, whose underlying mathematical foundations could not exist without appropriately called imaginary numbers (*page 106*).

Confounding these complexities is the work of Nobel-winning physicists who ran experiments on entangled photons and determined that objects may lack definite properties until they are observed (by us, namely). This work stemmed from the mystery of how quantum theory itself works (*page 24*). For every puzzle in physics, there is a team looking for an answer, which in turn cracks open a nesting doll of additional puzzles. And perhaps that is the most surprising thing about physics.

Andrea Gawrylewski
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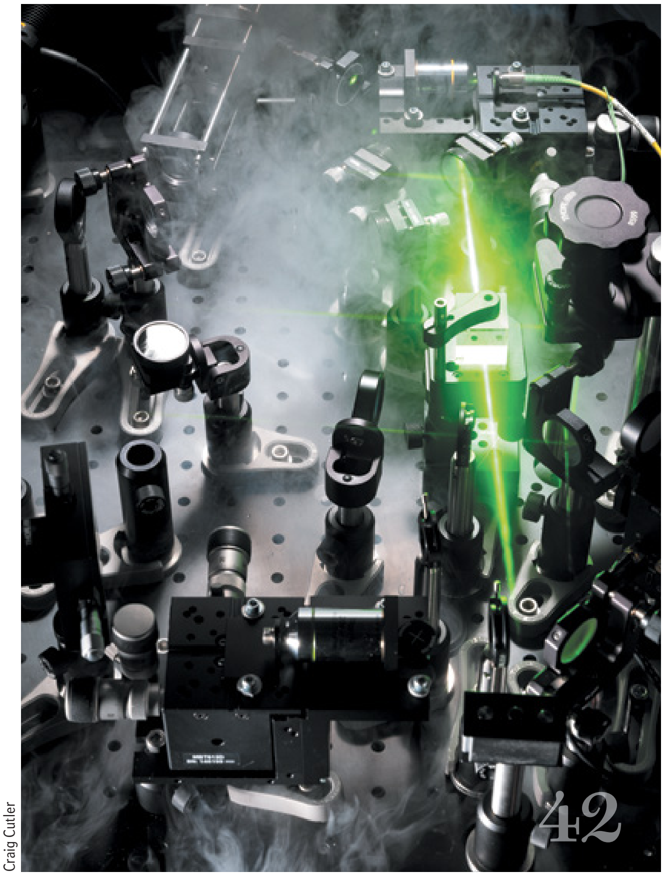
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BREAKING COSMOLOGY

JWST's first images included unimaginably distant galaxies that challenge theories of how quickly these structures can form

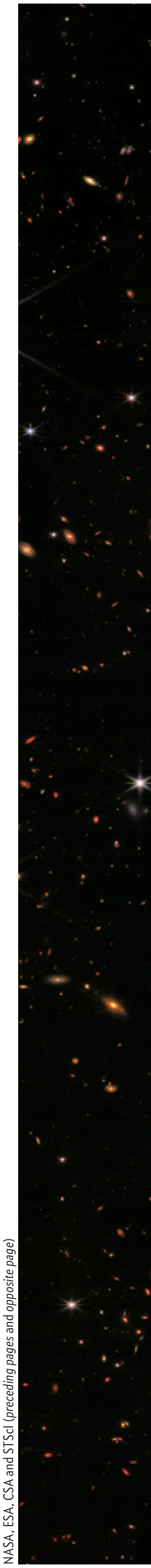
By Jonathan O'Callaghan

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GALAXIES from the depths of cosmic time appear in a small crop from "deep field" observations taken by the James Webb Space Telescope (JWST). The most distant objects in such images may reveal surprising new details about the early universe.

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NASA, ESA, CSA and STScI *(preceding pages and opposite page)*

ROHAN NAIDU WAS AT HOME WITH HIS GIRLFRIEND WHEN HE found the galaxy that nearly broke cosmology. As his algorithm dug through early images from the James Webb Space Telescope (JWST) late one night in July 2022, Naidu shot to attention. It had sifted out an object that Naidu recognized was inexplicably massive and dated back to just 300 million years after the big bang, making it older than any galaxy ever seen before. "I called my girlfriend over right away," Naidu says. "I told her, 'This might be the most distant starlight we've ever seen.'" After exchanging excited messages with one of his collaborators "with lots of exclamation marks," Naidu got to work. Days later they published a paper on the candidate galaxy, which they dubbed "GLASS-z13." The Internet exploded. "It reverberated around the world," Naidu says.

The discovery of this galaxy, just weeks into JWST's full operations, was beyond astronomers' wildest dreams. JWST—the largest, most powerful observatory ever launched from Earth—was built to revolutionize our understanding of the universe. Stationed 1.5 million kilometers away from earthly interference and chilled close to absolute zero by its tennis court–sized sunshade, the telescope's giant segmented mirror and exquisitely sensitive instruments were designed to uncover details of cosmic dawn never before observed.

This is the scarcely probed era—no more than a few hundred million years after the big bang itself—in which the very first stars and galaxies coalesced. How exactly this process unfolded depends on exotic physics, ranging from the uncertain influences of dark matter and dark energy to the poorly understood feedbacks between starlight, gas and dust. By glimpsing galaxies from cosmic dawn with JWST, cosmologists can test their knowledge of all these underlying phenomena—either confirming the validity of their best consensus models or revealing gaps in understanding that could herald profound new discoveries.

Such observations were supposed to take time; initial projections estimated the first galaxies would be so small and faint that JWST would find at best a few intriguingly remote candidates in its pilot investigations. Things didn't quite go as planned. Instead, as soon as the telescope's scientists released its very first images of the distant universe, astronomers such as Naidu (at the Massachusetts Institute of Technology) started finding numerous galaxies within them that, in apparent age, size and luminosity, surpassed all predictions. The competition for discovery was fierce: with each new day, it seemed, claims of yet

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THE INTERACTING galaxies of Stephan's Quintet, as seen by JWST, approximately 290 million light-years away from Earth. Covering one fifth of the moon's diameter, this mosaic is constructed from almost 1,000 separate images and reveals never-before-seen details of this galaxy group.

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NASA, ESA, CSA and STScI

another record-breaking “earliest known galaxy” emerged from one research group or another. “Everyone was freaking out,” says Charlotte Mason, an astrophysicist at the University of Copenhagen. “We really weren’t expecting this.”

In the weeks and months following JWST’s findings of surprisingly mature “early” galaxies, theorists and observers have been scrambling to explain them. Could the bevy of anomalously big and bright early galaxies be illusory, perhaps because of flaws in analysis of the telescope’s initial observations? If genuine, could they somehow be explained by standard cosmological models? Or, just maybe, were they the first hints that the universe is more strange and complex than even our boldest theories had supposed?

At stake is nothing less than our very understanding of how the orderly universe we know emerged from primordial chaos. JWST’s early revelations could rewrite the opening chapters of cosmic history, which concern not only distant epochs and faraway galaxies but also our own existence here in the familiar Milky Way. “You build these machines not to confirm the paradigm but to break it,” says JWST scientist Mark McCaughrean, a

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senior adviser for science and exploration at the European Space Agency. "You just don't know how it will break."

DEEP LOOKS FOR COSMIC DAWN

ONE MIGHT SAY JWST'S observations of early galaxies have been billions of years in the making, but more modestly they trace back to the Space Telescope Science Institute (STScI) in 1985. At the time the Hubble Space Telescope was still five years away from launching on a space shuttle. But Garth Illingworth, then deputy director of the STScI, was surprised one day when his boss, then director Riccardo Giacconi, who died in 2018, asked him to start thinking about what would come after Hubble much farther down the road. "I protested, saying we've got more than enough to do on Hubble," Illingworth recalls. But Giacconi was insistent: "Trust me, it'll take a long time," he

AN IMAGE FROM JWST reveals hundreds of previously invisible newborn stars in the stellar nursery known as the Carina Nebula, a vast agglomeration of gas and dust some 7,600 light-years from Earth.

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said. So, Illingworth and a handful of others got to work, drawing up concept ideas for what became known as the Next Generation Space Telescope (NGST), later renamed as JWST after a former NASA administrator.

Hubble would be transformational, but astronomers knew its capabilities would be limited by its observations in visible light. As light from a very distant galaxy travels across the cosmic abyss, it is stretched by the expansion of the universe—a broadening of wavelengths known as redshift. The higher the redshift value, the more stretching the light has experienced, and thus the more distant its source galaxy. Redshifts for early galaxies are so high that their emitted visible light has stretched into infrared by the time it arrives at our telescopes, which is why Hubble could not see them. The NGST, for comparison, would observe in infrared and would boast a very large (and very cold) starlight-gathering mirror, allowing it to peer much deeper into the universe. "Everybody realized that Webb would be the telescope for looking at early galaxies," Illingworth says. "That became the primary science goal."

The need for the telescope was highlighted in December 1995, when astronomers pointed Hubble at a seemingly empty patch of the sky for 10 consecutive days. Many experts predicted the extended observation would be a waste of resources, revealing at best a handful of dim galaxies, but instead the effort was richly rewarded. The resulting image, the Hubble Deep Field, showed the "empty" spot was filled with galaxies by the thousands, stretching back 12 billion years into the 13.8-billion-year history of our universe. "There were galaxies everywhere," says Illingworth, now an astrophysicist at the University of California, Santa Cruz. The Hubble Deep Field showed that the early universe was even more crowded and exciting than most anyone had expected, offering observational treasures to those who took the time and care to properly look. Yet, impressive as Hubble's Deep Field was, astronomers wanted more.

After more than two decades of labor at a cost of some $10 billion, JWST finally launched on Christmas Day 2021. The telescope reached its deep-space destination a month later, where it would endure exhaustive testing to ensure its optimal performance. By July 2022 it was ready to begin its long-awaited first year of science observations, known as Cycle 1. Part of the telescope's early time was devoted to high-impact programs across a range of disciplines from which data would immediately be made public. Two of those, CEERS (the Cosmic Evolution Early Release Science Survey) and GLASS (the Grism Lens–Amplified Survey from Space), independently spent dozens of hours looking for galaxies in the early universe by staring at separate small portions of the sky. Not much was expected—perhaps a slightly more ornate version of the Hubble Deep Field but nothing more. Steven Finkelstein of the University of Texas at Austin, the lead on CEERS, says extremely distant galaxies were predicted to pop up only "after a few cycles of data" from multiple programs.

Instead, much to the surprise of astronomers, extremely distant galaxies came into view immediately. Hubble's record for the most distant known galaxy had been GN-z11, spotted in 2015 at a redshift of 11 thanks to a 2009 upgrade that enhanced the telescope's modest infrared capabilities. A redshift of 11 corresponds to a cosmic age of about 400 million years, a point at the brink of when galaxy formation was thought to begin. But



from the very first GLASS data, two teams—one led by Naidu in that breathless late-night discovery—independently found GLASS-z13 at a redshift of 13, some 70 million years farther back in time.

In their quest for quick results, the researchers relied on redshift estimates derived from simple brightness-based measurements. These are easier to obtain but less precise than direct measurements of redshift, which require more dedicated observation time. Nevertheless, the simplified technique can be accurate, and here it suggested a galaxy that was unexpectedly bright and big, already bearing a mass of stars equivalent to a billion suns, just a few hundred times less than that of the Milky Way's stellar population, despite our own galaxy being billions of years more mature. "This was beyond our most optimistic expectations," says Tommaso Treu, an astronomer at the University of California, Los Angeles, and the lead on GLASS.

The record didn't last long. In the following days, dozens of galaxy candidates from CEERS and GLASS sprang into view with estimated redshifts as high as 20—just 180 million years after the big bang—some with disklike structures that were not expected to manifest so early in cosmic history. Another team, meanwhile, found evidence for galaxies the size of our Milky Way at a redshift of 10, less than 500 million years after the big bang.

Such behemoths emerging so rapidly defies expectations set by cosmologists' standard model of the universe's evolution. Called Lambda CDM (LCDM), this model incorporates scientists' best estimates for the properties of dark energy and dark matter, which collectively act to dominate the emergence of large-scale cosmic structures. ("Lambda" refers to dark energy, and "CDM" refers to dark matter that is relatively sluggish, or "cold.") "Even if you took everything that was available to form

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A SIDE-BY-SIDE COMPARISON shows JWST's remarkably detailed observations of the Southern Ring Nebula in near-infrared light (*left*) and mid-infrared light (*right*). Located more than 2,000 light-years from Earth, the nebula is composed of shells of gas and dust expelled from a dying star, which in each image can be seen near the nebula's core.

stars and snapped your fingers instantaneously, you still wouldn't be able to get that big that early," says Michael Boylan-Kolchin, a cosmologist at the University of Texas at Austin. "It would be a real revolution."

HOW TO BUILD A GALAXY

TO UNDERSTAND THE DILEMMA, a brief refresher is needed. In the first second after the big bang, our universe was an almost inconceivably hot and dense soup of primordial particles. Over the next three minutes, as the cosmos expanded and cooled, the nuclei of helium and other very light elements began to form. Fast-forward 400,000 years, and the universe was cold enough for the first atoms to appear. When the universe was about 100 million years old, theorists say, conditions were finally right for the emergence of the first stars. These giant fireballs of mostly hydrogen and helium were uncontaminated by heavier elements found in modern-day stars, so they possessed significantly different properties. Larger and brighter than today's stars, these first suns coalesced in protogalaxies—clusters of gas that clung to vast, invisible scaffolds of dark matter. Gravity guided the subsequent interactions between these protogalaxies, which eventually merged to form larger galaxies. This process of becoming, of the early universe's chaos giving way to the more orderly cosmos we know today, is thought to have taken about a billion years.

JWST's discovery of bright galaxies in the early cosmos challenges this model. "We should see lots of these little protogalactic fragments that have not yet merged to make a big galaxy," says Stacy McGaugh, a cosmologist at Case Western Reserve University. "Instead we're seeing a few things that are already big galaxies." Some of these galaxies may be impostors, much closer galaxies shrouded in dust that makes them look dimmer and farther away when brightness-based measurements are used. Follow-up observations of GLASS-z13 in August 2022 by the Atacama Large Millimeter Array (ALMA) in Chile, however, suggest that is not the case for this candidate, because ALMA did not see evidence for large amounts of dust. "I think we can exclude low-redshift interlopers," says Tom Bakx, an astronomer at Nagoya University in Japan, who led the observations. Yet the lack of dust means ALMA struggled to see the galaxy at all, showing how difficult it could be for telescopes to confirm observations made using JWST's advanced capabilities. "The good news is there's nothing detected," Naidu says. "The bad news is there's nothing detected." Only JWST, in this case, can follow up itself.

The most startling explanation is that the canonical LCDM cosmological model is wrong and requires revision. "These results are very surprising and hard to get in our standard model of cosmology," Boylan-Kolchin says. "And it's probably not a small change. We'd have to go back to the drawing board." One controversial idea is modified Newtonian dynamics (MOND), which posits that dark matter does not exist and that its effects can instead be explained by large-scale fluctuations in gravity. To date, JWST's observations could support such a theory. "MOND has had a lot of its predictions come true—this is another one of them," says McGaugh, who is one of the idea's leading proponents. Others remain unconvinced. "So far everything that we've tried to test MOND hasn't been able to really provide a satisfactory answer," says Jeyhan Kartaltepe, an astrophysicist at the Rochester Institute of Technology.

One simpler solution is that galaxies in the early universe could have little or no dust, making them appear brighter. This scenario could confound efforts to calculate the galaxies' true masses and could perhaps also explain ALMA's difficulty spotting GLASS-z13. "It could be that supernovae didn't have enough time to produce the dust, or maybe in the initial phases [of galaxy formation] the dust is expelled from galaxies," says Andrea Ferrara, an astronomer at the Scuola Normale Superiore in Italy, who has proposed such a possibility. Alternatively, Mason and her colleagues suggest that in its observations of the early universe JWST may so far be seeing only the very brightest young galaxies, as they should be the easiest to spot. "Maybe there's something happening in the early universe that means it's easier for some galaxies to form stars," she says.

David Spergel, a theoretical astrophysicist and current president of the Simons Foundation in New York City, agrees. "I think what we're seeing is that high-mass star formation is very efficient in the early universe," he says. "The gas pressures are higher. The temperatures are higher. That has an enormous impact on the environment for star formation." Magnetic fields might have arisen earlier in the universe than we thought, driving material to kick-start the birth of stars. "We might be seeing a signature of magnetic fields emerging very early in the universe's history," Spergel says.

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A RUSH TO BREAK THE UNIVERSE

THE RAPID FLOW of scientific papers from JWST's initial observations is no fluke; when the first data arrived, astronomers were eagerly waiting. "People had been working on their pipelines for years," Boylan-Kolchin says. Instead of the traditional peer-review process, which can take months, astronomers published on arXiv, a website where scientific papers can be uploaded after minimal review by moderators but well before formal peer review. This new form of review is unfolding in near real time on X (formerly Twitter) and other social media platforms. "It's science by arXiv," Naidu says. The resulting frenzy was intense—and surprising. "I expected a lot of activity," says Nancy Levenson, STScI's interim director. "But I underestimated the amount."

The result was that scientific results could be rapidly publicized and discussed, but some fear at a cost. "People were rushing things a little bit," says Klaus Pontoppidan, JWST's project scientist at STScI. "The gold standard is a refereed, peer-reviewed paper." Early calibration issues with JWST, for example, may have affected some results. Nathan Adams of the University of Manchester in England and his colleagues found there could be dramatic changes, with one galaxy at a redshift of 20.4 recalibrated to a redshift of just 0.7. "We need to calm down a little bit," Adams says. "It's a bit too early to say we've completely broken the universe."

Such issues are unlikely to eradicate all of JWST's high-redshift galaxies, however, given their sheer number. "It's more likely that the early universe is different from what we predicted," Finkelstein says. "The odds are small that we're all wrong." Astronomers are now racing to conduct follow-up observations with JWST. Levenson says she's currently reviewing about a dozen proposals from various groups asking for additional JWST observing time, most of which are seeking to scrutinize high-redshift galaxy candidates. "Considering the excitement and importance of these early discoveries, we thought it was appropriate to ask for a little bit of time to confirm them," says Treu, who put forward one of the proposals.

More programs have been designed to hunt for distant galaxies, such as COSMOS-Webb, co-led by Kartaltepe, which aims to hugely increase the known population of early galaxies by observing a wider swath of sky for hundreds of hours. "We estimate there are thousands we'll be able to detect," she says. Future proposals might look for evidence of those first protogalaxies, perhaps using the explosive deaths of supersized first stars in especially luminous and energetic supernovae as markers for their existence. Some estimates suggest JWST could see as far as a redshift of 26, just 120 million years after the big bang, a cosmic blink of an eye. Much other work will be done to follow up the growing list of high-redshift candidates. "Even confirming a handful of these would be quite amazing," Naidu says. "It would demonstrate we're not getting fooled."

JWST has ushered in a new era of science, and despite the uncertainties, the rapid communication of new discoveries has invigorated astronomers. "It's been fantastic," Treu says. "It's really wonderful to see the community so engaged and excited." Now the question is, If we can truly believe what we are seeing, is it time to reappraise our understanding of the dawn of time? "We're peering into the unknown," Mason says. SA

Jonathan O'Callaghan is a freelance journalist covering commercial spaceflight, space exploration and astrophysics.



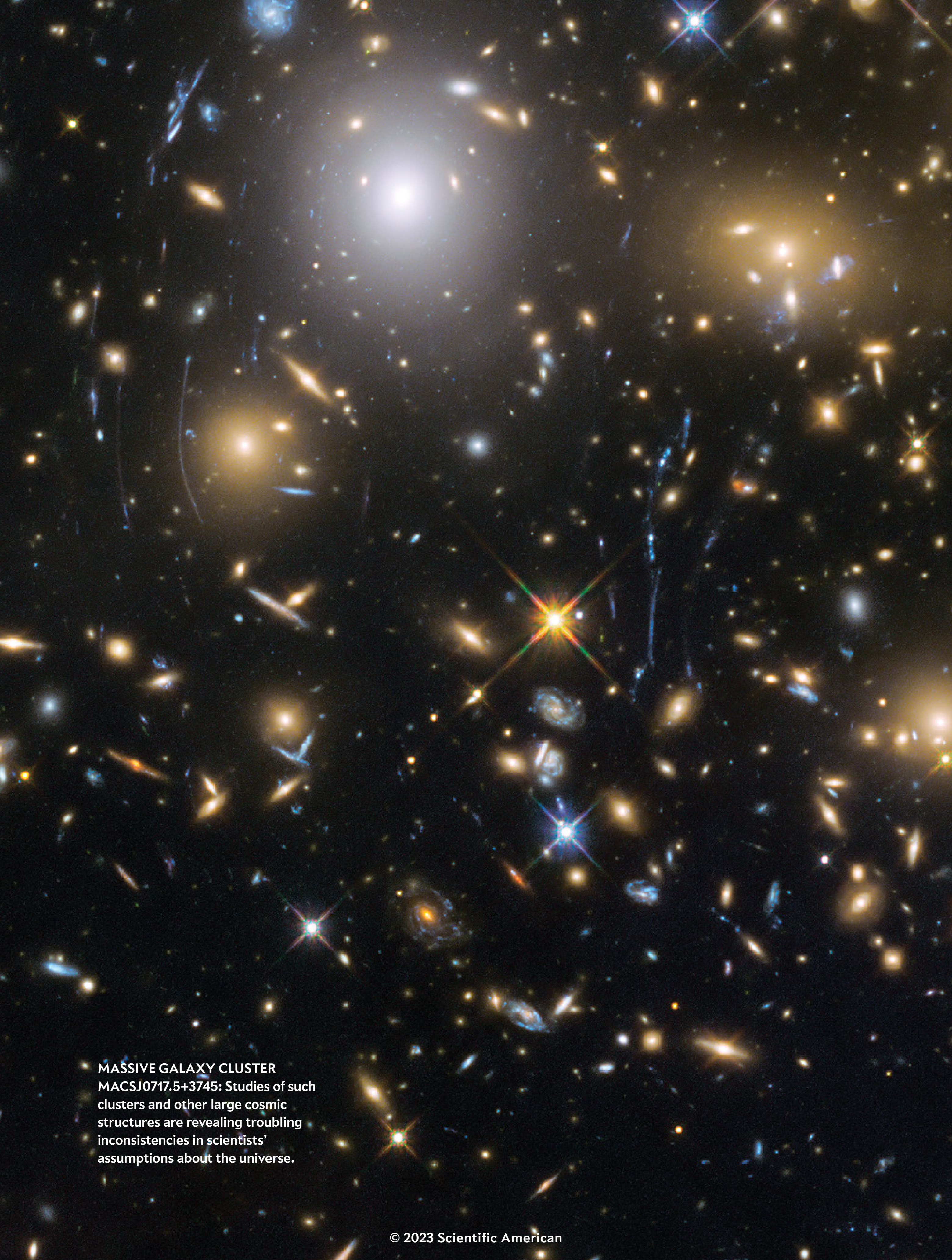
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THE CARTWHEEL GALAXY displays its characteristic dust-rich "spokes" and starry inner and outer rings in this near-infrared view from JWST. These features ripple like shock waves from the galaxy's center, the site of a high-speed collision with another galaxy some 400 million years ago.

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MASSIVE GALAXY CLUSTER MACSJ0717.5+3745: Studies of such clusters and other large cosmic structures are revealing troubling inconsistencies in scientists' assumptions about the universe.

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TWIN TENSIONS

A debate over conflicting measurements of key cosmological properties is poised to shape the next decade of astronomy and astrophysics

By Anil Ananthaswamy

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HOW FAST IS THE UNIVERSE EXPANDING? HOW MUCH DOES MATTER CLUMP up in our cosmic neighborhood? Scientists use two methods to answer these questions. One involves observing the early cosmos and extrapolating to present times, and the other makes direct observations of the nearby universe. But there is a problem. The two methods consistently yield different answers. The simplest explanation for these discrepancies is merely that our measurements are somehow erroneous, but researchers are increasingly entertaining another, more breathtaking possibility: These twin tensions—between expectation and observation, between the early and late universe—may reflect some deep flaw in the standard model of cosmology, which encapsulates our knowledge and assumptions about the universe. Finding and fixing that flaw could transform our understanding of the cosmos.

One way or another, an answer seems certain to emerge over the coming decade, as new space and terrestrial telescopes give astronomers clearer cosmic views. "Pursuing these tensions is a great way to learn about the universe," says astrophysicist and Nobel laureate Adam Riess of Johns Hopkins University. "They give us the ability to focus our experiments on very specific tests, rather than just making it a general fishing expedition."

These new telescopes, Riess anticipates, are about to usher in the third generation of precision cosmology. The first generation came in the 1990s and early 2000s with the Hubble Space Telescope and with NASA's WMAP satellite, which sharpened our measurements of the universe's oldest light, the cosmic microwave background (CMB). This first generation was also shaped by eight-meter-class telescopes in Chile and the twin 10-meter Keck behemoths in Hawaii. PDF Downloaded@mobilism.org

Collectively, these observatories helped scientists formulate the standard model of cosmology, which holds that the universe is a cocktail of 5 percent ordinary matter, 27 percent dark matter and 68 percent dark energy. This model can account with uncanny accuracy for most of what we observe about galaxies, galaxy clusters, and other large-scale structures and their evolution over cosmic time. Ironically, by its very success, the model highlights what we do not know: the exact nature of 95 percent of the universe.

Driven by even more precise measurements of the CMB from the European Space Agency's Planck satellite and various ground-based telescopes, the second generation of precision cosmology supported the standard model but also brought to light the tensions. The focus shifted to reducing so-called systematics: repeatable errors that creep in because of faults in the design of experiments or equipment.

The third generation is only now starting to take the stage with the successful launch and deep-space deployment of Hubble's successor, the James Webb Space Telescope (JWST). On Earth, radio telescope arrays such as the Simons Observatory in the Atacama Desert in Chile and the CMB-S4, a future assemblage of 21 dishes and half a million cryogenically cooled detectors that will be divided between sites in the Atacama and at the South Pole, should take CMB measurements with Planck-surpassing levels of precision.

The centerpieces of the third generation will be telescopes that stare at wide swaths of the sky. The first of these is the ESA's 1.2-meter Euclid space telescope, which launched in July 2023. Euclid will study the shapes and distributions of billions of galaxies with a gaze that spans about a third of the sky. Its observations will dovetail with those of NASA's Nancy Grace Roman Space Telescope, a 2.4-meter telescope with a field of view about 100 times bigger than Hubble's, which is slated for launch in 2026 or 2027. Finally, when it begins operations in the mid-2020s, the ground-based Vera C. Rubin Observatory in Chile will map the entire overhead sky every few nights with its 8.4-meter mirror and a three-billion-pixel camera, the largest ever built for astronomy. "We're not going to be limited by noise and by systematics, because these are independent observatories," says astrophysicist Priyamvada Natarajan of Yale University. "Even if we have a systematic in our framework, we should [be able to] figure it out."

SCALING THE DISTANCE LADDER

RIESS WOULD LIKE to see a resolution of the Hubble tension, which arises from differing estimates of the value of the Hubble constant, H_0—the rate at which the universe is expanding. Riess leads a project called Supernovae, H_0, for the Equation of State of Dark Energy (SH0ES). The goal is to measure H_0, starting with the first rung of the so-called cosmic distance ladder, a hierarchy of methods to gauge ever greater celestial expanses.

The first rung—the one concerning the nearest cosmic objects—relies on determining the distance to special stars called

NASA/ESA/HST Frontier Fields Team (STScI) *(preceding pages)*

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A NOCTURNAL VIEW of the South Pole Telescope, one of several radio observatories mapping patterns in the cosmic microwave background.

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Cepheid variables, which pulsate in proportion to their intrinsic luminosity. The longer the pulsation, the brighter the Cepheid. This relation between variability and luminosity makes Cepheids benchmark "standard candles" for determining distances around the Milky Way and nearby galaxies. They also form the basis of the cosmic distance ladder's second rung, in which astronomers gauge distances to more remote galaxies by comparing Cepheid-derived estimates with those from another, more powerful set of standard candles called type Ia (pronounced "one A") supernovae, or SNe Ia.

Ascending farther, astronomers locate SNe Ia in even more far-flung galaxies, using them to establish a relation between distance and a galaxy's redshift, a measure of how fast it is moving away from us. The result is an estimate of H_0.

In December 2021, Riess says, "after a couple of years of taking a deep dive on the subject," the SH0ES team and the Pantheon+ team, which has compiled a large data set of type Ia supernovae, announced the results of nearly 70 different analyses of their combined data. The data included observations of Cepheid variables in 37 host galaxies that contained 42 type Ia supernovae, more than double the number of supernovae studied by SH0ES in 2016. Riess and his co-authors suspect this study represents the Hubble's last stand, the outer limits of that hallowed telescope's ability to help them climb higher up the cosmic scale. The set of supernovae now includes "all suitable SNe Ia—of which we are aware—observed between 1980 and 2021" in the nearby universe. In their analysis, H_0 comes out to be 73.04 ± 1.04 kilometers per second per megaparsec.

That number is way off the value obtained by an entirely different method that looks at the other end of cosmic history—the so-called epoch of recombination, when the universe became transparent to light, about 380,000 years after the big bang. The light from this epoch, now stretched to microwave wavelengths because of the universe's subsequent expansion, is detectable as the all-pervading cosmic microwave background. Tiny fluctuations in temperature and polarization of the CMB capture an important signal: the distance a sound wave travels from almost the beginning of the universe to the epoch of recombination.

This length is a useful metric for precision cosmology and can be used to estimate the value of H_0 by extrapolating to the present-day universe using the standard LCDM model. (L stands for lambda or dark energy, and CDM for cold dark matter; "cold" refers to the assumption that dark matter particles are relatively slow-moving.) An analysis published in 2021 combined data from the Planck satellite and two ground-based instruments, the Atacama Cosmology Telescope and the South Pole Telescope, to arrive at an H_0 of 67.49 ± 0.53.

The discrepancy between the two estimates has a statistical significance of five sigma, meaning there is only about a one-in-a-million chance of its being a statistical fluke. "It's certainly at the level that people should take seriously," Riess says. "And they have."

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HOW CLUMPY IS THE COSMOS?

THE OTHER TENSION that researchers are starting to take seriously concerns a cosmic parameter called S_8, which depends on the density of matter in the universe and the extent to which it is clumped up rather than evenly distributed. Estimates of S_8 also involve, on one end, measurements of the CMB and, on the other, measurements of the local universe. The CMB-derived value of S_8 in the early universe, extrapolated using LCDM, generates a present-day value of about 0.834.

The local universe measurements of S_8 involve a host of different methods. Among the most stringent are so-called weak gravitational lensing observations, which measure how the average shape of millions of galaxies across large patches of the sky is distorted by the gravitational influence of intervening concentrations of dark and normal matter. Astronomers used data from the Kilo-Degree Survey, which more than doubled its sky coverage from 350 to 777 square degrees of the sky (the full moon, by comparison, spans a mere half a degree) and estimated S_8 to be about 0.759. The tension between the early- and late-universe estimates of S_8 grew from 2.5 sigma in 2019 to three sigma (or a one-in-740 chance of being a fluke). "This tension isn't going away," says astronomer Hendrik Hildebrandt of Ruhr University Bochum in Germany. "It has hardened."

> "We don't know why dark energy is the dominant component of the universe today."
> —David Spergel *Princeton University*

There is yet another way to arrive at the value of S_8: by counting the number of the most massive galaxy clusters in some volume of space. Astronomers can do that directly—for example, by using gravitational lensing. They can also count clusters by studying their imprint on the cosmic microwave background, thanks to something called the Sunyaev-Zeldovich effect. (This effect causes CMB photons to scatter off the hot electrons in clusters of galaxies, creating shadows in the CMB that are proportional to the mass of the cluster.)

A detailed 2019 study that used data from the South Pole Telescope estimated S_8 to be 0.749—again, way off from the CMB+LCDM-based estimates. These numbers could be reconciled if the estimates of the masses of these clusters were wrong by about 40 to 50 percent, Natarajan says, although she thinks such substantial revisions are unlikely. "We are not that badly off in the measurement game," she says. "So that's another kind of internal inconsistency, another anomaly pointing to something else."

BREAKING THE TENSIONS

GIVEN THESE TENSIONS, it is no surprise that cosmologists are anxiously awaiting fresh data from the new generation of observatories. For instance, David Spergel of Princeton University is eager for astronomers to use JWST to study the brightest of the so-called red-giant-branch stars. These stars have a well-known luminosity and can be used as standard candles to measure galactic distances—an independent rung on the cosmic ladder, if you will. In 2019 Wendy Freedman of the University of Chicago and her colleagues used this technique to estimate H_0, finding that their value sat smack in the middle of the early- and late-universe estimates. "The error bars on the current tip of the red-giant-branch data are such that they're consistent with both possibilities," Spergel says. Astronomers are also planning to use JWST to recalibrate the Cepheids surveyed by Hubble, and separately the telescope will help create another new rung for the distance ladder by targeting Mira stars (which, like Cepheids, have a luminosity-periodicity relation useful for cosmic cartography).

JWST might resolve or strengthen the H_0 tension, and the wide-field survey data from the Euclid, Roman and Rubin observatories could do the same for the S_8 tension by studying the clustering and clumping of matter. The sheer amount of data expected from this trio of telescopes will reduce S_8 error bars enormously. "The statistics are going to go through the roof," Natarajan says.

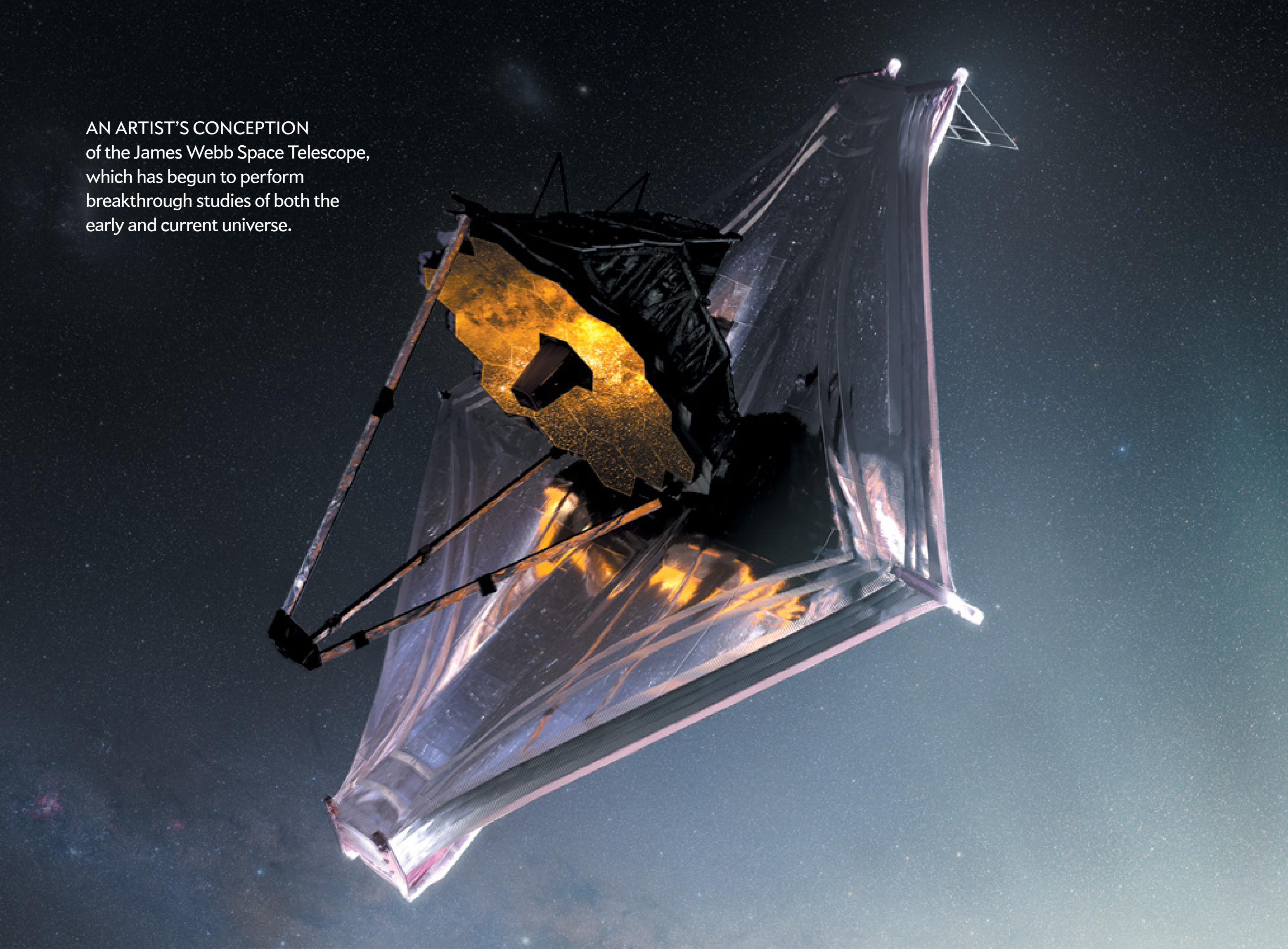
Meanwhile theoreticians are already having a field day with the twin tensions. "This is a playground for theorists," Riess says. "You throw in some actual observed tensions, and they are having more fun than we are."

One of the most recent theoretical ideas to receive a great deal of interest is something called early dark energy (EDE). In the canonical LCDM model, dark energy started dominating the universe relatively late in cosmic history, only about five billion years ago. But, Spergel says, "we don't know why dark energy is the dominant component of the universe today. Because we don't know why it's important today, it could have also been important early on." That is partly the rationale for invoking dark energy's effects much earlier, before the epoch of recombination. Even if dark energy was just 10 percent of the universe's energy budget during those times, that would be enough to accelerate the early phases of cosmic expansion, causing recombination to occur sooner and shrinking the distance traversed by primordial sound waves. The net effect would be to ease the H_0 tension.

"What I find most interesting about these models is that they can be wrong," Spergel says. Cosmologists' EDE models make predictions about the resulting EDE-modulated patterns in the photons of the CMB. In February 2022 Silvia Galli, a member of the Planck collaboration at the Sorbonne University in Paris, and her colleagues published an analysis of observations from Planck and ground-based CMB telescopes, suggesting that they collectively favor EDE over LCDM by a statistical smidgen. Confirming or refuting this tentative result will require more and better data—which could come from observations by the same ground-based CMB telescopes. But even if EDE models prove to be better fits and fix the H_0 tension, they do little to alleviate the tension from S_8.

Potential fixes for S_8 exhibit a similarly vexing lack of overlap with H_0. In March 2022 Guillermo Franco Abellán of the University of Amsterdam and his colleagues published a study in *Physical Review D* showing that the S_8 tension could be eased by the hypothetical decay of cold dark matter particles into one massive particle and one "warm" massless particle. This mechanism would lower the value of S_8 arising from CMB-based extrapolations, bringing it more in line with the late-universe measurements. Unfortunately, it doesn't solve the H_0 tension. "It seems like a robust pattern: whatever model you come up with that solves the H_0 tension makes the S_8 tension worse, and the other way around," Hildebrandt says. "There are a few models that at least don't make the other tension worse, but [they] also don't improve it a lot."

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AN ARTIST'S CONCEPTION of the James Webb Space Telescope, which has begun to perform breakthrough studies of both the early and current universe.

NASA/GSFC/CIL/Adriana Manrique Gutierrez

"WE ARE MISSING SOMETHING"

ONCE FRESH DATA arrive, Spergel foresees a few possible scenarios. First, the new CMB data could turn out to be consistent with early dark energy, resolving the H_0 tension, and the upcoming survey telescope observations could separately ease the S_8 tension. That would be a win for early dark energy models—and would constitute a major shift in our understanding of the opening chapters of cosmic history. It's also possible that both H_0 and S_8 tensions will resolve in favor of LCDM—a win for the cosmological standard model and a possibly bittersweet victory for cosmologists hoping for paradigm-shifting breakthroughs. Of course, it might turn out that neither tension is resolved. "Outcome three would be both tensions become increasingly significant as the data improve—and early dark energy isn't the answer," Spergel says. Then, LCDM would presumably have to be reworked differently, although how is unclear.

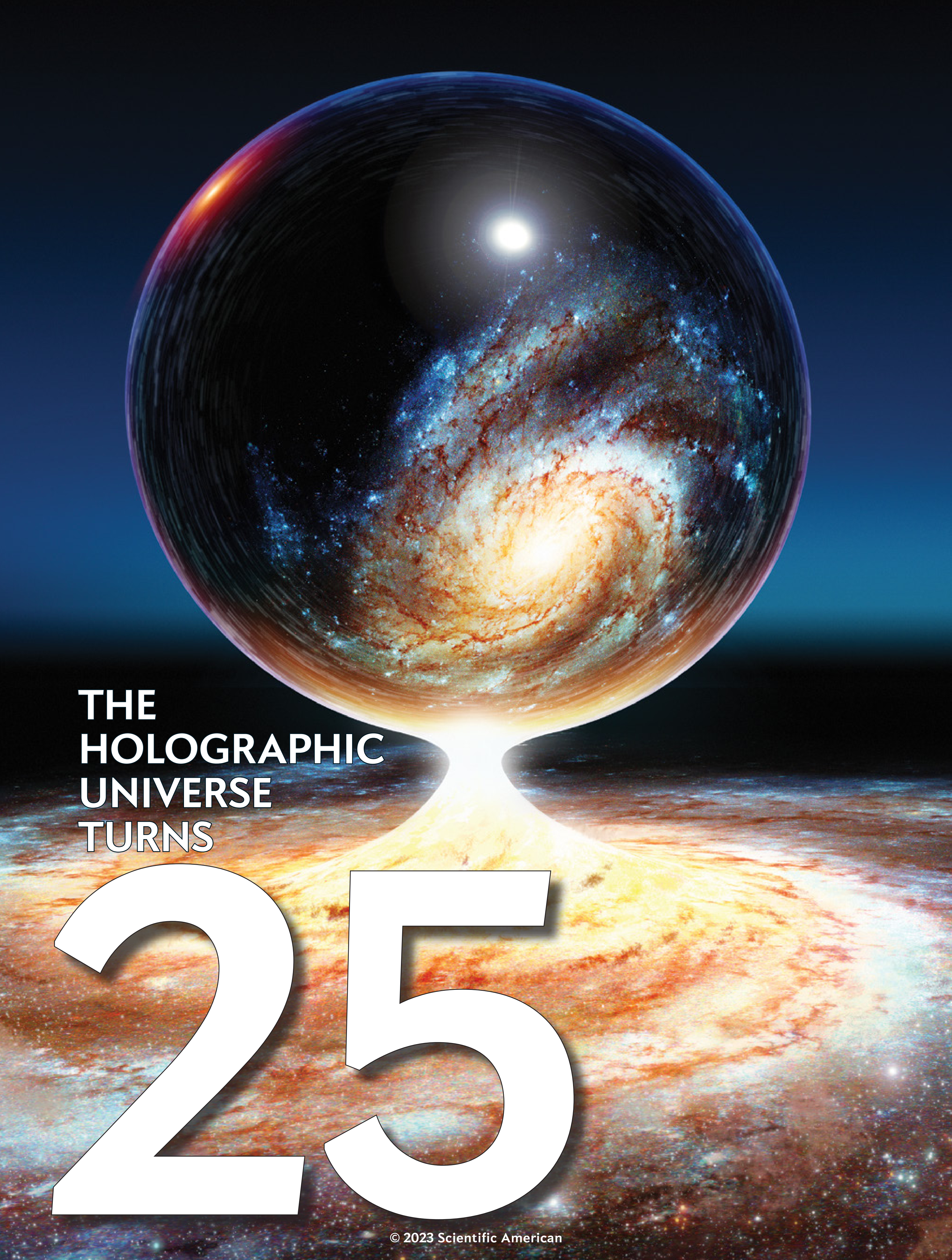
Natarajan thinks that the tensions and discrepancies are probably telling us that LCDM is merely an "effective theory," a technical term meaning that it accurately explains a certain subset of the current compendium of cosmic observations. "Perhaps what's really happening is that there is an underlying, more complex theory," she says. "And that LCDM is this [effective] theory, which seems to have most of the key ingredients. For the level of observational probes we had previously, that effective theory was sufficient." But times change, and the data deluge from precision cosmology's third generation of powerful observatories may demand more creative and elaborate theories.

Theorists, of course, are happy to oblige. For instance, Spergel speculates that if early dark energy could interact with dark matter (in LCDM, dark energy and dark matter do not interact), this arrangement could suppress the fluctuations of matter in the early universe in ways that would resolve the S_8 tension while simultaneously taking care of the H_0 tension. "It makes the models more baroque," Spergel says, "but maybe that's what nature will demand."

As an observational astronomer, Hildebrandt is circumspect. "If there was a convincing model that beautifully solves these two tensions, we'd already have the next standard model," he says. "That we're instead still talking about these tensions and scratching our heads is just reflecting the fact that we don't have such a model yet." Riess agrees. "After all, this is a problem of using a model based on an understanding of physics and the universe that is about 95 percent incomplete, in terms of the nature of dark matter and dark energy," he says. "It wouldn't be crazy to think that we are missing something." SA

Anil Ananthaswamy is author of *The Edge of Physics* (Houghton Mifflin Harcourt, 2010), *The Man Who Wasn't There* (Dutton, 2015), and, most recently, *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality* (Dutton, 2018).

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The Ads/CFT duality conjecture, which suggests our universe is a hologram, has enabled many significant discoveries in physics

By Anil Ananthaswamy

Illustration by Kenn Brown/Mondolithic Studios

A QUARTER OF A CENTURY AGO a conjecture shook the world of theoretical physics. It had the aura of revelation. "At first, we had a magical statement … almost out of nowhere," says Mark Van Raamsdonk, a theoretical physicist at the University of British Columbia. The idea, put forth by Juan Maldacena of the Institute for Advanced Study in Princeton, N.J., suggested something profound: that our universe could be a hologram. Much like a 3-D hologram emerges from the information encoded on a 2-D surface, our universe's 4-D spacetime could be a holographic projection of a lower-dimensional reality.

Specifically, Maldacena showed that a five-dimensional theory of a type of imaginary spacetime called anti–de Sitter space (AdS) that included gravity could describe the same system as a lower-dimensional quantum field theory of particles and fields in the absence of gravity, referred to as a conformal field theory (CFT). In other words, he found two different theories that could describe the same physical system, showing that the theories were, in a sense, equivalent—even though they included different numbers of dimensions, and one factored in gravity where the other didn't. Maldacena then surmised that this AdS/CFT duality would hold for other pairs of theories in which one had a single extra dimension, possibly even those describing 4-D spacetime akin to ours.

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The conjecture was both intriguing and shocking. How could a theory that included gravity be the same as a theory that had no place for gravity? How could they describe the same universe? But the duality has largely held up. In essence, it argues that we can understand what happens inside a volume of spacetime that has gravity by studying the quantum-mechanical behavior of particles and fields at that volume's surface, using a theory with one less dimension, one in which gravity plays no role. "Sometimes some things are easier to understand in one description than the other, and knowing that you're really talking about the same physics is very powerful," says Netta Engelhardt, a theoretical physicist at the Massachusetts Institute of Technology.

In the 25 years since Maldacena proposed the idea, physicists have used this power to address questions about whether black holes destroy information, to better understand an early epoch in our universe's history called inflation, and to arrive at an astonishing conclusion that spacetime may not be fundamental—it may be something that emerges from quantum entanglement in a lower-dimensional system. These advances all involve the theoretically plausible spacetime of anti–de Sitter space, which is not the de Sitter space that describes our universe. But physicists are optimistic that they'll one day arrive at a duality that works for both. If that were to happen, it could lead to a theory of quantum gravity, which would combine Einstein's general relativity with quantum mechanics. It would also imply that our universe is in truth a hologram.

THE ORIGINS OF HOLOGRAPHY

IN DEVISING THE DUALITY, Maldacena was inspired by work by the late theoretical physicist Joseph Polchinski of the University of California, Santa Barbara. Using string theory, in which reality arises from the vibration of impossibly tiny strings, Polchinski developed a theory of objects called D-branes, which serve as the end points for strings that don't close in on themselves.

Maldacena looked at the conformal field theory describing D-branes without gravity on the one hand and an AdS theory with one more dimension of space and including gravity on the other. Maldacena noticed similarities between the two. Both theories were scale invariant, meaning the physics of the systems the theories described didn't change as the systems got larger or smaller. The lower-dimensional theory also had an additional symmetry—conformal invariance—where the physical laws don't change for all transformations of spacetime that preserve angles. The AdS theory describing the same objects in the presence of gravity showed similar symmetries. "That these two [theories] have the same symmetries was an important clue," Maldacena says.

The differences between the two theories were equally important. Crucially, the quantum field theory of D-branes was strongly coupled, meaning that particles and fields in the theory interacted strongly with one another. The AdS theory was weakly coupled—particles and fields interacted feebly. A lower-dimensional, weakly coupled CFT and its higher-dimensional, strongly coupled AdS counterpart share the same inverse relationship. Making a calculation is simpler in the weakly coupled system, but because the theories are equivalent, the results can apply to the strongly coupled theory without the need for often impossible calculations.

Maldacena described his discovery in a paper that he submitted to a preprint website in November 1997 and eventually published in the *International Journal of Theoretical Physics*. The idea took some time to sink in. "There were hundreds, thousands of papers, just checking [the duality] because at first, it [seemed] so ridiculous that some nongravitational quantum theory could actually just be the same thing as a gravitational theory," Van Raamsdonk says. But AdS/CFT held up to scrutiny, and soon theorists were using it to answer some confounding questions.

One of the first uses of AdS/CFT involved understanding black holes. In the 1970s Stephen Hawking showed that black holes emit thermal radiation, in the form of particles, because of quantum-mechanical effects near the event horizon. Eventually this "Hawking" radiation would cause a black hole to evaporate—which posed a problem. What happens to the information contained in the matter that formed the black hole? Is that information lost forever? Such a loss would go against the laws of quantum mechanics, which say that information cannot be destroyed.

In 2006 physicists Shinsei Ryu and Tadashi Takayanagi, then both at the University of California's Kavli Institute for Theoretical Physics, used the AdS/CFT duality to establish a connection between two numbers, one in each theory. One pertains to a special type of surface in the volume of spacetime described by AdS. Say there's a black hole in the AdS theory. It has a surface, called an extremal surface, which is the boundary around the black hole where spacetime makes the transition from weak to strong curvature (this surface may or may not lie inside the black hole's event horizon). The other number, which pertains to the quantum system being described by the CFT, is called entanglement entropy—it's a measure of how much one part of the quantum system is entangled with the rest. The Ryu-Takayanagi result showed that the area of the extremal surface of a black hole in the AdS is related to the entanglement entropy of the quantum system in the CFT.

The Ryu-Takayanagi conjecture promised something alluring. As a black hole evaporates in AdS, the area of its extremal surface changes. As this area changes, so does the entanglement entropy calculated in the CFT. But however the entanglement changes, the holographic surface described by the CFT evolves according to the rules of quantum mechanics, meaning that information is never lost. This equivalence implied that black holes in AdS were also not losing information. There was a hitch, though. The Ryu-Takayanagi formula works only in the absence of quantum effects in the AdS theory. "And of course, if a black hole is evaporating, it is evaporating as a result of small quantum corrections," Engelhardt says. "So we can't use Ryu-Takayanagi."

In 2014 Engelhardt and Aron Wall of the University of Cambridge found a way to calculate the extremal surface area of a black hole that is subject to the kind of quantum corrections that cause Hawking radiation. Then, in 2019, Engelhardt and her colleagues, along with another researcher working independently, showed that the area of these quantum extremal surfaces can be used to calculate the entanglement entropy of the Hawking radiation in the CFT and that this quantity does indeed follow the dictates of quantum mechanics, consistent with no loss of information. (They also found that the quantum extremal surface lies within the black hole's event horizon.) "This finally gave us a link between something geometric—these quantum extremal surfaces—and something that's a litmus test of information conservation, which is the behavior of the entropy [when] information is conserved," Engelhardt says. "Without AdS/CFT, I doubt we'd have arrived at these conclusions."

The connection between entanglement entropy in the CFT and the geometry of spacetime in the AdS led to another impor-

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tant result—the notion that spacetime on the AdS side emerges from quantum entanglement on the CFT side, not just in black holes but throughout the universe. The idea is best understood by analogy. Think of a very dilute gas of water molecules. Physicists can't describe this system using the equations of hydrodynamics, because the dilute gas does not behave like a liquid. But suppose the water molecules condense into a pool of liquid water. Now those very same molecules are subject to the laws of hydrodynamics. "You could ask, originally, where was that hydrodynamics?" Van Raamsdonk says. "It just wasn't relevant."

Something similar happens in AdS/CFT. On the CFT side, you can start with quantum subsystems—smaller subsets of the overall system you're describing—each with fields and particles, without any entanglement. In the equivalent AdS description, you'd have a system with no spacetime. Without spacetime, Einstein's general relativity isn't relevant, in much the same way that the equations of hydrodynamics don't apply to a gas of water molecules. But when the entanglement on the CFT side starts increasing, the entanglement entropy of the quantum subsystems begins to correspond to patches of spacetime that emerge in the AdS description. These patches are physically disconnected from each other. Going from patch A to patch B isn't possible without leaving both A and B; however, each individual patch can be described using general relativity.

Now increase the entanglement of the quantum subsystems in the CFT even more, and something intriguing happens in the AdS: the patches of spacetime begin connecting. Eventually you end up with a contiguous volume of spacetime. "When you have the right pattern of entanglement, you start to get a spacetime on the other side," Van Raamsdonk says. "It's almost like the spacetime is a geometric representation of the entanglement. Take away all the entanglement, and then you just eliminate the spacetime." Engelhardt agrees: "Entanglement between quantum systems is important for the existence and emergence of spacetime." The duality suggested that the spacetime of our physical universe might simply be an emergent property of some underlying, entangled part of nature.

Van Raamsdonk credits the AdS/CFT correspondence for making physicists question the very nature of spacetime. If spacetime emerges from the degree and nature of entanglement in a lower-dimensional quantum system, it means that the quantum system is more "real" than the spacetime we live in, in much the same way that a 2-D postcard is more real than the 3-D hologram it creates. "That [space itself and the geometry of space] should have something to do with quantum mechanics is just really shocking," he says.

TOWARD A THEORY OF QUANTUM GRAVITY

ONCE SPACETIME emerges in a theory, physicists can use it to study aspects of our universe. For example, our cosmos is thought to have expanded exponentially in the first fractions of a second of its existence during inflation. In the standard model of cosmology, theorists start with a spacetime in which particles and fields interact weakly and let inflation proceed for about 50 to 60 "*e*-folds," where each *e*-fold represents more than a doubling of the volume of spacetime (as it increases by a factor of Euler's number *e*, or approximately 2.718). Such inflation can replicate the properties of the observed universe, such as its flatness and isotropy (the fact that it looks the same in all directions).

But there's no reason to think that inflation stops at 60 *e*-folds. What if it goes on for longer? It turns out that if physicists design models of our universe in which inflation goes on for, say, 70 *e*-folds or more, then the initial state of the universe must be strongly coupled—that is, it has to be one in which fields and particles can interact strongly with each other. A model that allows for this prolonged expansion would be more general (meaning it could apply to multiple possible versions of the universe), but calculations involving strongly coupled spacetimes are nearly impossible to compute. And that's where the AdS/CFT approach comes in.

Horatiu Nastase of São Paulo State University–International in Brazil has shown how to use the AdS/CFT duality to study a strongly coupled initial state of the universe. It's possible because the CFT side of the duality turns out to be weakly coupled, making calculations tractable. These calculations can then be used to determine the state of the AdS after, say, 70-plus *e*-folds. Nastase has found that a strongly coupled spacetime that inflates for at least 72 *e*-folds can replicate certain observations from our own cosmos, with some fine-tuning of the model's parameters. In particular, the model can match the kind of fluctuations seen in the cosmic microwave background, the fossil radiation from the big bang. "This is ongoing work," Nastase says. "There are a number of issues that are not yet clear."

Physicists hope that insights like these will get them to a theory of quantum gravity for our own universe. The lack of such a theory is one of the biggest open problems in physics. One fundamental insight from AdS/CFT is that any theory of quantum gravity will most likely be holographic, in that it'll have a dual description in the form of a theory with one fewer dimension, without gravity.

The AdS/CFT community is working hard to generalize the correspondence to spacetimes that are more representative of our universe. In AdS, researchers can create a spacetime with cosmic constituents such as black holes, but the spacetime has to be "asymptotically empty," which means that as one goes farther and farther away from a black hole, space becomes empty. "In describing our own universe, we assume that there's stuff everywhere as far as you go," Van Raamsdonk says. "You're never going to run out of galaxies." Also, in AdS, empty space has negative curvature, whereas the empty de Sitter space of our universe is mostly flat.

As influential as AdS/CFT has proved, the duality still uses a spacetime that does not describe our own reality. Maldacena hopes researchers will find a similar correspondence between de Sitter space—the spacetime we occupy—and a CFT. "I would very much like to have [a] similar statement for de Sitter," he says. "People keep thinking about it, but no clear contender has emerged so far."

Van Raamsdonk is optimistic that such a candidate will emerge. "If it turns out our own universe has some underlying holographic description, if this is really how it works, then I think understanding AdS/CFT will be at the level of understanding quantum mechanics, at the level of understanding general relativity," he says. "[It would be] as big of a leap in our understanding of the universe as anything else that's happened in the history of physics." SA

Anil Ananthaswamy is author of *The Edge of Physics* (Houghton Mifflin Harcourt, 2010), *The Man Who Wasn't There* (Dutton, 2015), and *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality* (Dutton, 2018).

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The Universe Is Not Locally Real



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Experiments with entangled light have revealed a profound mystery at the heart of reality

By Daniel Garisto

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ONE OF THE MORE UNSETTLING DISCOVERIES IN THE PAST HALF a century is that the universe is not locally real. In this context, "real" means that objects have definite properties independent of observation—an apple can be red even when no one is looking. "Local" means that objects can be influenced only by their surroundings and that any influence cannot travel faster than light. Investigations at the frontiers of quantum physics have found that these things cannot both be true. Instead the evidence shows that objects are *not* influenced solely by their surroundings, and they *may* also lack definite properties prior to measurement.

This is, of course, deeply contrary to our everyday experiences. As Albert Einstein once bemoaned to a friend, "Do you really believe the moon is not there when you are not looking at it?" To adapt a phrase from author Douglas Adams, the demise of local realism has made a lot of people very angry and has been widely regarded as a bad move.

Blame for this achievement has been laid squarely on the shoulders of three physicists: John Clauser, Alain Aspect and Anton Zeilinger. They equally split the 2022 Nobel Prize in Physics "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science." ("Bell inequalities" refers to the pioneering work of physicist John Stewart Bell of Northern Ireland, who laid the foundations for the 2022 Physics Nobel in the early 1960s.) Colleagues agreed that the trio had it coming, deserving this reckoning for overthrowing reality as we know it. "It was long overdue," says Sandu Popescu, a quantum physicist at the University of Bristol in England. "Without any doubt, the prize is well deserved."

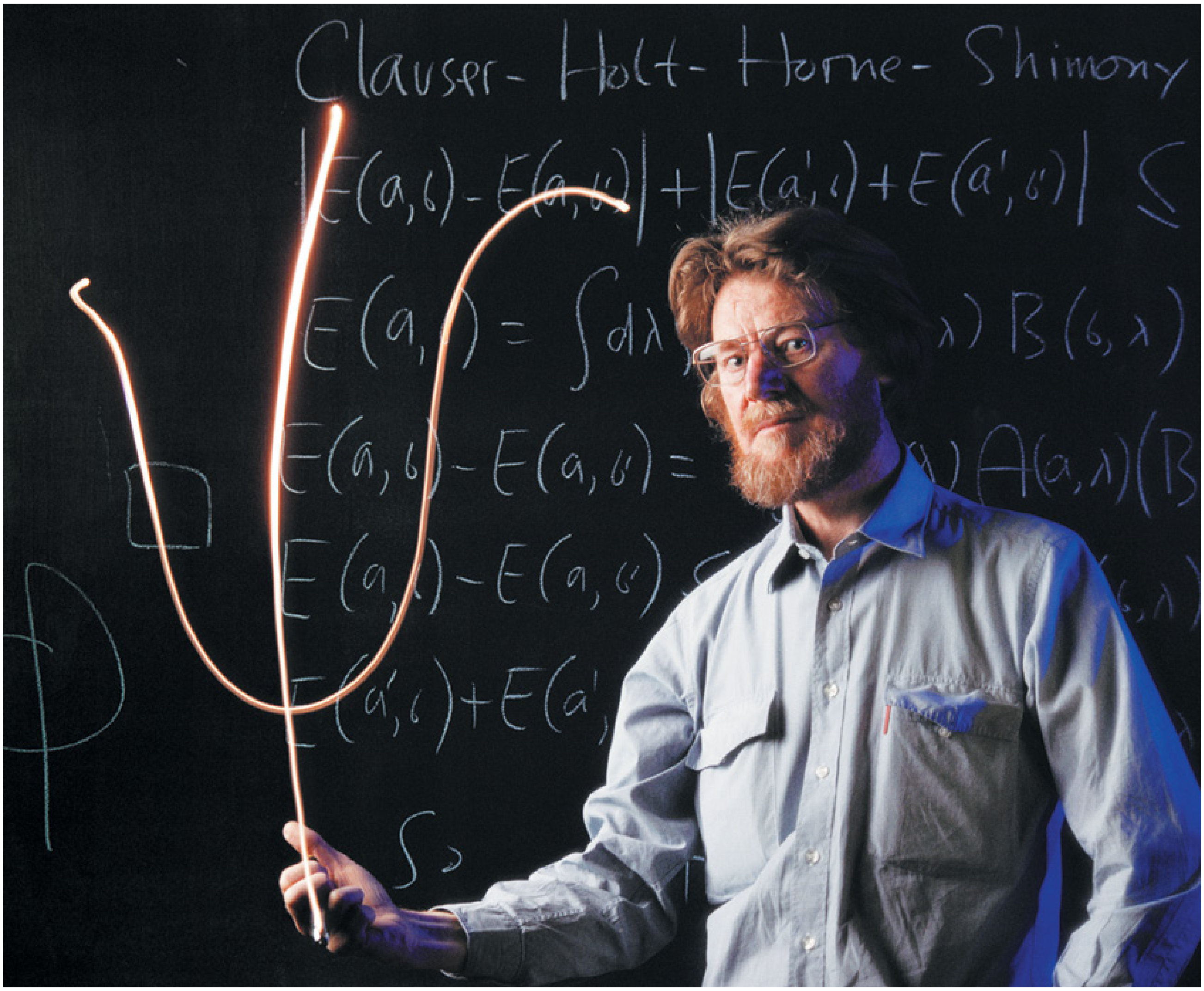
"The experiments beginning with the earliest one of Clauser and continuing along show that this stuff isn't just philosophical, it's real—and like other real things, potentially useful," says Charles Bennett, an eminent quantum researcher at IBM. "Each year I thought, 'Oh, maybe this is the year,'" says David Kaiser, a physicist and historian at the Massachusetts Institute of Technology. "[In 2022] it really was. It was very emotional—and very thrilling."

The journey from fringe to favor was a long one. From about 1940 until as late as 1990, studies of so-called quantum foundations were often treated as philosophy at best and crackpottery at worst. Many scientific journals refused to publish papers on the topic, and academic positions indulging such investigations were nearly impossible to come by. In 1985 Popescu's adviser warned him against a Ph.D. in the subject. "He said, 'Look, if you do that, you will have fun for five years, and then you will be jobless,'" Popescu says.

Today quantum information science is among the most vibrant subfields in all of physics. It links Einstein's general theory of relativity with quantum mechanics via the still mysterious behavior of black

Athul Satheesh/500px/Getty Images (*preceding pages*)

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WORK BY John Stewart Bell in the 1960s sparked a quiet revolution in quantum physics.

Peter Menzel/Science Source

holes. It dictates the design and function of quantum sensors, which are increasingly being used to study everything from earthquakes to dark matter. And it clarifies the often confusing nature of quantum entanglement, a phenomenon that is pivotal to modern materials science and that lies at the heart of quantum computing. "What even makes a quantum computer 'quantum?'" Nicole Yunger Halpern, a physicist at the National Institute of Standards and Technology, asks rhetorically. "One of the most popular answers is entanglement, and the main reason why we understand entanglement is the grand work participated in by Bell and these Nobel Prize winners. Without that understanding of entanglement, we probably wouldn't be able to realize quantum computers."

FOR WHOM THE BELL TOLLS

THE TROUBLE WITH quantum mechanics was never that it made the wrong predictions—in fact, the theory described the microscopic world splendidly right from the start when physicists devised it in the opening decades of the 20th century. What Einstein, Boris Podolsky and Nathan Rosen took issue with, as they explained in their iconic 1935 paper, was the theory's uncomfortable implications for reality. Their analysis, known by their initials EPR, centered on a thought experiment meant to illustrate the absurdity of quantum mechanics. The goal was to show how under certain conditions the theory can break—or at least deliver nonsensical results that conflict with our deepest assumptions about reality.

A simplified and modernized version of EPR goes something like this: Pairs of particles are sent off in different directions from a common source, targeted for two observers, Alice and Bob, each stationed at opposite ends of the solar system. Quantum mechanics dictates that it is impossible to know the spin, a quantum property of individual particles, prior to measurement. Once Alice measures one of her particles, she finds its spin to be either "up" or "down." Her results are random, and yet when she measures up, she instantly knows that Bob's corresponding particle—which had a random, indefinite spin—must now be down. At first glance, this is not so odd. Maybe the

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particles are like a pair of socks—if Alice gets the right sock, Bob must have the left.

But under quantum mechanics, particles are not like socks, and only when measured do they settle on a spin of up or down. This is EPR's key conundrum: If Alice's particles lack a spin until measurement, then how (as they whiz past Neptune) do they know what Bob's particles will do as they fly out of the solar system in the other direction? Each time Alice measures, she quizzes her particle on what Bob will get if he flips a coin: up or down? The odds of correctly predicting this even 200 times in a row are one in 10^{60}—a number greater than all the atoms in the solar system. Yet despite the billions of kilometers that separate the particle pairs, quantum mechanics says Alice's particles can keep correctly predicting, as though they were telepathically connected to Bob's particles.

Designed to reveal the incompleteness of quantum mechanics, EPR eventually led to experimental results that instead reinforce the theory's most mind-boggling tenets. Under quantum mechanics, nature is not locally real: particles may lack properties such as spin up or spin down prior to measurement, and they seem to talk to one another no matter the distance. (Because the outcomes of measurements are random, these correlations cannot be used for faster-than-light communication.)

Physicists skeptical of quantum mechanics proposed that this puzzle could be explained by hidden variables, factors that existed in some imperceptible level of reality, under the subatomic realm, that contained information about a particle's future state. They hoped that in hidden variable theories, nature could recover the local realism denied it by quantum mechanics. "One would have thought that the arguments of Einstein, Podolsky and Rosen would produce a revolution at that moment, and everybody would have started working on hidden variables," Popescu says.

Einstein's "attack" on quantum mechanics, however, did not catch on among physicists, who by and large accepted quantum mechanics as is. This was less a thoughtful embrace of nonlocal reality than a desire not to think too hard—a head-in-the-sand sentiment later summarized by American physicist N. David Mermin as a demand to "shut up and calculate." The lack of interest was driven in part because John von Neumann, a highly regarded scientist, had in 1932 published a mathematical proof ruling out hidden variable theories. Von Neumann's proof, it must be said, was refuted just three years later by a young female mathematician, Grete Hermann, but at the time no one seemed to notice.

The problem of nonlocal realism would languish for another three decades before being shattered by Bell. From the start of his career, Bell was bothered by quantum orthodoxy and sympathetic toward hidden variable theories. Inspiration struck him in 1952, when he learned that American physicist David Bohm had formulated a viable nonlocal hidden variable interpretation of quantum mechanics—something von Neumann had claimed was impossible.

Bell mulled the ideas for years, as a side project to his job working as a particle physicist at CERN near Geneva. In 1964 he rediscovered the same flaws in von Neumann's argument that Hermann had. And then, in a triumph of rigorous thinking, Bell concocted a theorem that dragged the question of local hidden variables from its metaphysical quagmire onto the concrete ground of experiment.

Typically local hidden variable theories and quantum mechanics predict indistinguishable experimental outcomes. What Bell realized is that under precise circumstances, an empirical discrepancy between the two can emerge. In the eponymous Bell test (an evolution of the EPR thought experiment), Alice and Bob receive the same paired particles, but now they each have two different detector settings—A and a, B and b. These detector settings are an additional trick to throw off Alice and Bob's apparent telepathy. In local hidden variable theories, one particle cannot know which question the other is asked. Their correlation is secretly set ahead of time and is not sensitive to updated detector settings. But according to quantum mechanics, when Alice and Bob use the same settings (both uppercase or both lowercase), each particle is aware of the question the other is posed, and the two will correlate perfectly—in sync in a way no local theory can account for. They are, in a word, entangled.

Measuring the correlation multiple times for many particle pairs, therefore, could prove which theory was correct. If the correlation remained below a limit derived from Bell's theorem, this would suggest hidden variables were real; if it exceeded Bell's limit, then the mind-boggling tenets of quantum mechanics would reign supreme. And yet, in spite of its potential to help determine the nature of reality, Bell's theorem languished unnoticed in a relatively obscure journal for years.

THE BELL TOLLS FOR THEE

IN 1967 A GRADUATE STUDENT at Columbia University named John Clauser accidentally stumbled across a library copy of Bell's paper and became enthralled by the possibility of proving hidden variable theories correct. When Clauser wrote to Bell two years later, asking if anyone had performed the test, it was among the first feedback Bell had received.

Three years after that, with Bell's encouragement, Clauser and his graduate student Stuart Freedman performed the first Bell test. Clauser had secured permission from his supervisors but little in the way of funds, so he became, as he said in a later interview, adept at "dumpster diving" to obtain equipment—some of which he and Freedman then duct-taped together. In Clauser's setup—a kayak-sized apparatus requiring careful tuning by hand—pairs of photons were sent in opposite directions toward detectors that could measure their state, or polarization.

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Unfortunately for Clauser and his infatuation with hidden variables, once he and Freedman completed their analysis, they had to conclude that they had found strong evidence against them. Still, the result was hardly conclusive because of various "loopholes" in the experiment that conceivably could allow the influence of hidden variables to slip through undetected. The most concerning of these was the locality loophole: if either the photon source or the detectors could have somehow shared information (which was plausible within an object the size of a kayak), the resulting measured correlations could still emerge from hidden variables. As M.I.T.'s Kaiser explained, if Alice tweets at Bob to tell him her detector setting, that interference makes ruling out hidden variables impossible.

Closing the locality loophole is easier said than done. The detector setting must be quickly changed while photons are on the fly—"quickly" meaning in a matter of mere nanoseconds. In 1976 a young French expert in optics, Alain Aspect, proposed a way for doing this ultra-speedy switch. His group's experimental results, published in 1982, only bolstered Clauser's results: local hidden variables looked extremely unlikely. "Perhaps Nature is not so queer as quantum mechanics," Bell wrote in response to Aspect's test. "But the experimental situation is not very encouraging from this point of view."

Other loopholes remained, however, and Bell died in 1990 without witnessing their closure. Even Aspect's experiment had not fully ruled out local effects, because it took place over too small a distance. Similarly, as Clauser and others had realized, if Alice and Bob detected an unrepresentative sample of particles—like a survey that contacted only right-handed people—their experiments could reach the wrong conclusions.

No one pounced to close these loopholes with more gusto than Anton Zeilinger, an ambitious, gregarious Austrian physicist. In 1997 he and his team improved on Aspect's earlier work by conducting a Bell test over a then unprecedented distance of nearly half a kilometer. The era of divining reality's nonlocality from kayak-sized experiments had drawn to a close. Finally, in 2013, Zeilinger's group took the next logical step, tackling multiple loopholes at the same time.

"Before quantum mechanics, I actually was interested in engineering. I like building things with my hands," says Marissa Giustina, a quantum researcher at Google who worked with Zeilinger. "In retrospect, a loophole-free Bell experiment is a giant systems-engineering project." One requirement for creating an experiment closing multiple loopholes was finding a perfectly straight, unoccupied 60-meter tunnel with access to fiber-optic cables. As it turned out, the dungeon of Vienna's Hofburg palace was an almost ideal setting—aside from being caked with a century's worth of dust. Their results, published in 2015, coincided with similar tests from two other groups that also found quantum mechanics as flawless as ever.

BELL'S TEST REACHES THE STARS

ONE GREAT FINAL LOOPHOLE remained to be closed—or at least narrowed. Any prior physical connection between components, no matter how distant in the past, has the possibility of interfering with the validity of a Bell test's results. If Alice shakes Bob's hand prior to departing on a spaceship, they share a past. It is seemingly implausible that a local hidden variable theory would exploit these loopholes, but it was still possible.

In 2016 a team that included Kaiser and Zeilinger performed a cosmic Bell test. Using telescopes in the Canary Islands, the researchers sourced its random decisions for detector settings from stars sufficiently far apart in the sky that light from one would not reach the other for hundreds of years, ensuring a centuries-spanning gap in their shared cosmic past. Yet even then, quantum mechanics again proved triumphant.

Today quantum information science is among the most vibrant subfields in all of physics.

One of the principal difficulties in explaining the importance of Bell tests to the public—as well as to skeptical physicists—is the perception that the veracity of quantum mechanics was a foregone conclusion. After all, researchers have measured many key aspects of quantum mechanics to a precision of greater than 10 parts in a billion. "I actually didn't want to work on it," Giustina says. "I thought, like, 'Come on, this is old physics. We all know what's going to happen.'" But the accuracy of quantum mechanics could not rule out the possibility of local hidden variables; only Bell tests could do that.

"What drew each of these Nobel recipients to the topic, and what drew John Bell himself to the topic, was indeed [the question], 'Can the world work that way?'" Kaiser says. "And how do we really know with confidence?" What Bell tests allow physicists to do is remove the bias of anthropocentric aesthetic judgments from the equation. They purge from their work the parts of human cognition that recoil at the possibility of eerily inexplicable entanglement or that scoff at hidden variable theories as just more debates over how many angels may dance on the head of a pin.

The award honors Clauser, Aspect and Zeilinger, but it is testament to all the researchers who were unsatisfied with superficial explanations about quantum mechanics and who asked their questions even when doing so was unpopular. "Bell tests," Giustina concludes, "are a very useful way of looking at reality." SA

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The Weight of Nothing

The Archimedes experiment aims to measure the void of empty space more precisely than ever before

By Manon Bischoff

Photographs by Vincent Fournier

A DUST SHEET shrouds the Archimedes experiment, which will try to weigh the "virtual particles" that fill empty space.

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IT DOES SOMETHING TO YOU WHEN YOU DRIVE IN HERE FOR THE FIRST TIME," ENRICO Calloni says as our car bumps down into the tunnel of a mine on the Italian island of Sardinia. After the intense heat aboveground, the contrast is stark. Within seconds, damp, cool air enters the car as it makes its way into the depths. "I hope you're not claustrophobic." This narrow tunnel, which leads us in almost complete darkness to a depth of 110 meters underground, isn't for everyone. But it's the ideal site for the project we are about to see—the Archimedes experiment, named after the ancient Greek scientist who first described its central principle, which aims to weigh "nothing."

The car stops, and our driver, Luca Loddo, gets out and equips everyone with helmets and flashlights. We cover the last part of the trip on foot, deeper and deeper into the tunnel. We pass a door to a room where seismographs record the subtle movements of the surrounding earth. Finally, a cave appears on the left side of the tunnel, with a spotlight pointing at it, and we stop. "This is where it's supposed to take place," explains Calloni, a physicist at the Italian National Institute of Nuclear Physics.

Geologically, Sardinia is one of the quietest places in Europe. The island, along with its neighbor Corsica, is located on a particularly secure block of Earth's crust that is among the most stable areas of the Mediterranean, with very few earthquakes in its entire recorded history and only one (offshore) event that ever reached the relatively mild category of magnitude 5. Physicists chose this geologically uneventful place because the Archimedes experiment requires extreme isolation from the outside environment. It involves a high-precision experimental setup designed to investigate the worst theoretical prediction in the history of physics—the amount of energy in the empty space that fills the universe.



Researchers can calculate the energy of the vacuum in two ways. From a cosmological perspective, they can use Albert Einstein's equations of general relativity to calculate how much energy is needed to explain the fact that the universe is expanding at an accelerated rate. They can also work from the bottom up, using quantum field theory to predict the value based on the masses of all the "virtual particles" that can briefly arise and then disappear in "empty" space (more on this later). These two methods produce numbers that differ by more than 120 orders of magnitude (1 followed by 120 zeros). It's an embarrassingly absurd discrepancy that has important implications for our understanding of the expansion of the universe—and even its ultimate fate. To figure out where the error lies, scientists decided to haul a two-meter-tall cylindrical vacuum chamber and other equipment down into an old Sardinian mine where they could attempt to create their own vacuum and weigh the nothing inside.

WHAT'S IN EMPTY SPACE?

A VACUUM is not completely empty. This is because of an idea in quantum physics called Heisenberg's uncertainty principle. The principle states that you can't determine the position and the velocity of a particle at the same time with any precision—the more precisely you know one value, the less precisely you can know the other. This principle also applies to other measurements, such as those involving energy and time. Its consequences are considerable. It means that nature can "borrow" energy for extremely short amounts of time. These changes in energy, known as vacuum fluctuations, often take the form of virtual particles, which can appear out of nowhere and disappear again immediately.

Vacuum fluctuations have to respect some rules. A single electrical charge, for example, cannot suddenly appear where there

Map by Jo Hannah Asetre

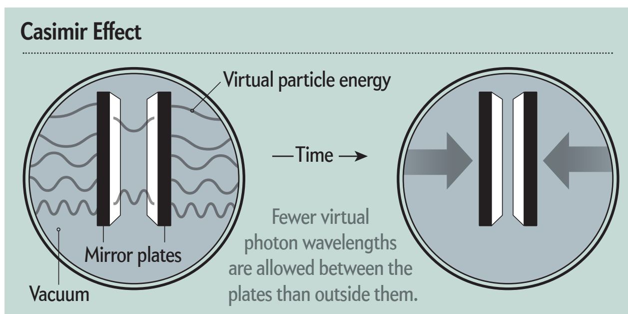
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PHYSICIST ENRICO CALLONI leads a team aiming to measure a minute signal with a complex and sensitive beam balance.

was none (this would violate the law of charge conservation). This means that only electrically neutral particles such as photons can pop out of the vacuum by themselves. Electrically charged particles have to emerge paired with their antiparticle matches. An electron, for instance, can appear along with a positron, which is positively charged; the two charges cancel each other out to preserve the total charge of zero. The result is that the vacuum is continuously filled with a stream of short-lived particles buzzing around.

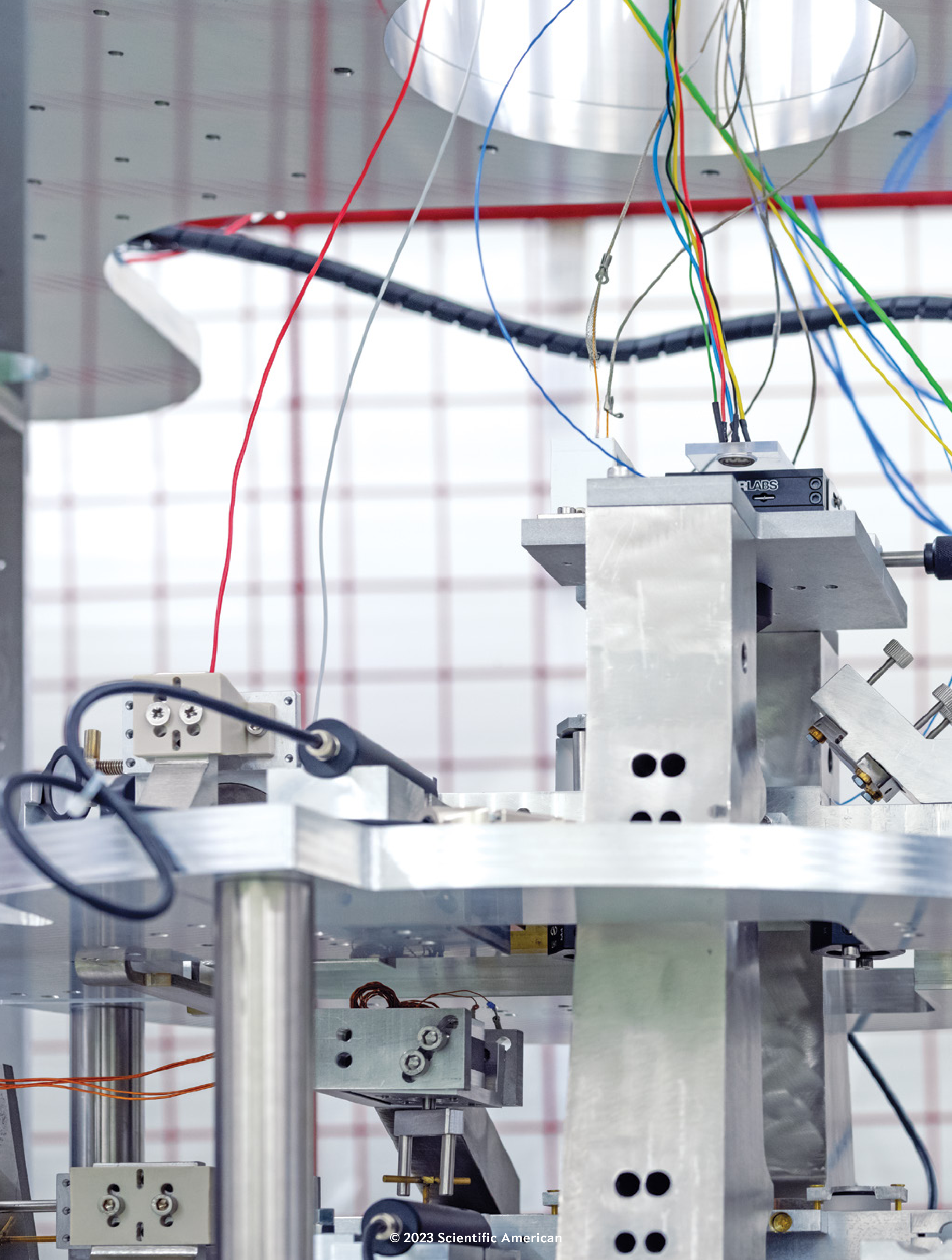
Even if we can't capture these virtual particles in detectors, their presence is measurable. One example is the Casimir effect, predicted by Dutch physicist Hendrik Casimir in 1948. According to his calculations, two opposing metal plates should attract each other in a vacuum, even without taking into account the slight gravitational pull they exert on each other. The reason? Virtual particles. The presence of the plates imposes certain limits on which virtual particles can emerge from the vacuum. For example, photons (particles of light) with certain energies can't appear between the plates. That's because the metal plates act like mirrors that reflect the photons back and forth. Photons with certain wavelengths will end up with wave troughs overlapping wave crests, effectively canceling themselves out. Other wavelengths will be amplified if two wave peaks overlap. The result is that certain energies are preferred, and others are suppressed as if those photons were never there. This means that only virtual particles with certain energy values can exist between the plates. Outside them, however, any virtual particles can emerge.



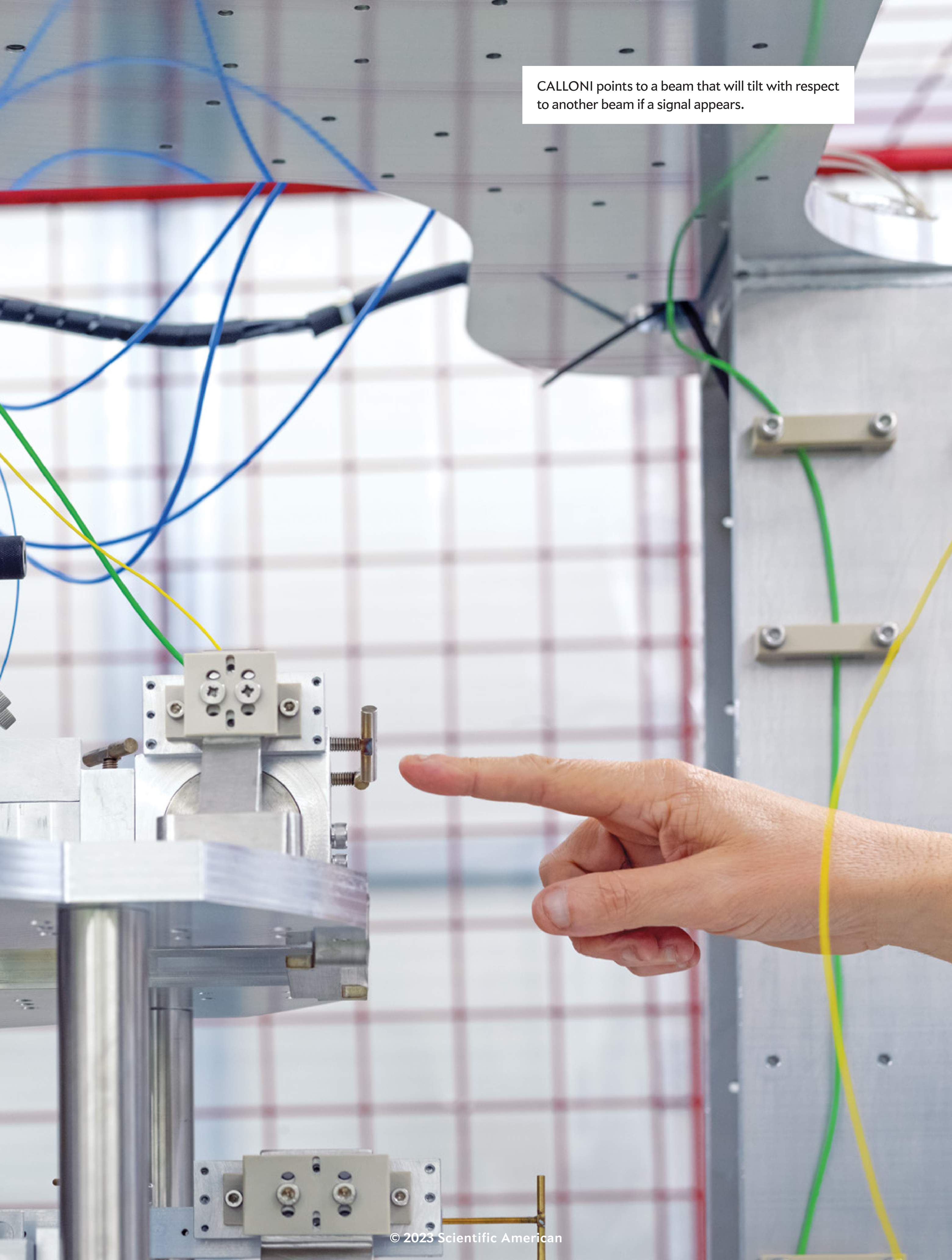
The result is that there are fewer possibilities—and therefore fewer virtual particles—between the plates than around them. The comparative abundance of particles on the outside exerts pressure on the plates, pressing them together. This effect, strange as it may sound, is measurable. Physicist Steven Lamoreaux confirmed the phenomenon experimentally at the University of Washington in 1997, almost 50 years after Casimir's prediction. Now Calloni and his colleagues hope to use the Casimir effect to measure the energy of the void.

This energy has important consequences for the universe as a whole. General relativity tells us that energy (for example, in the form of mass) curves spacetime. That means virtual particles,

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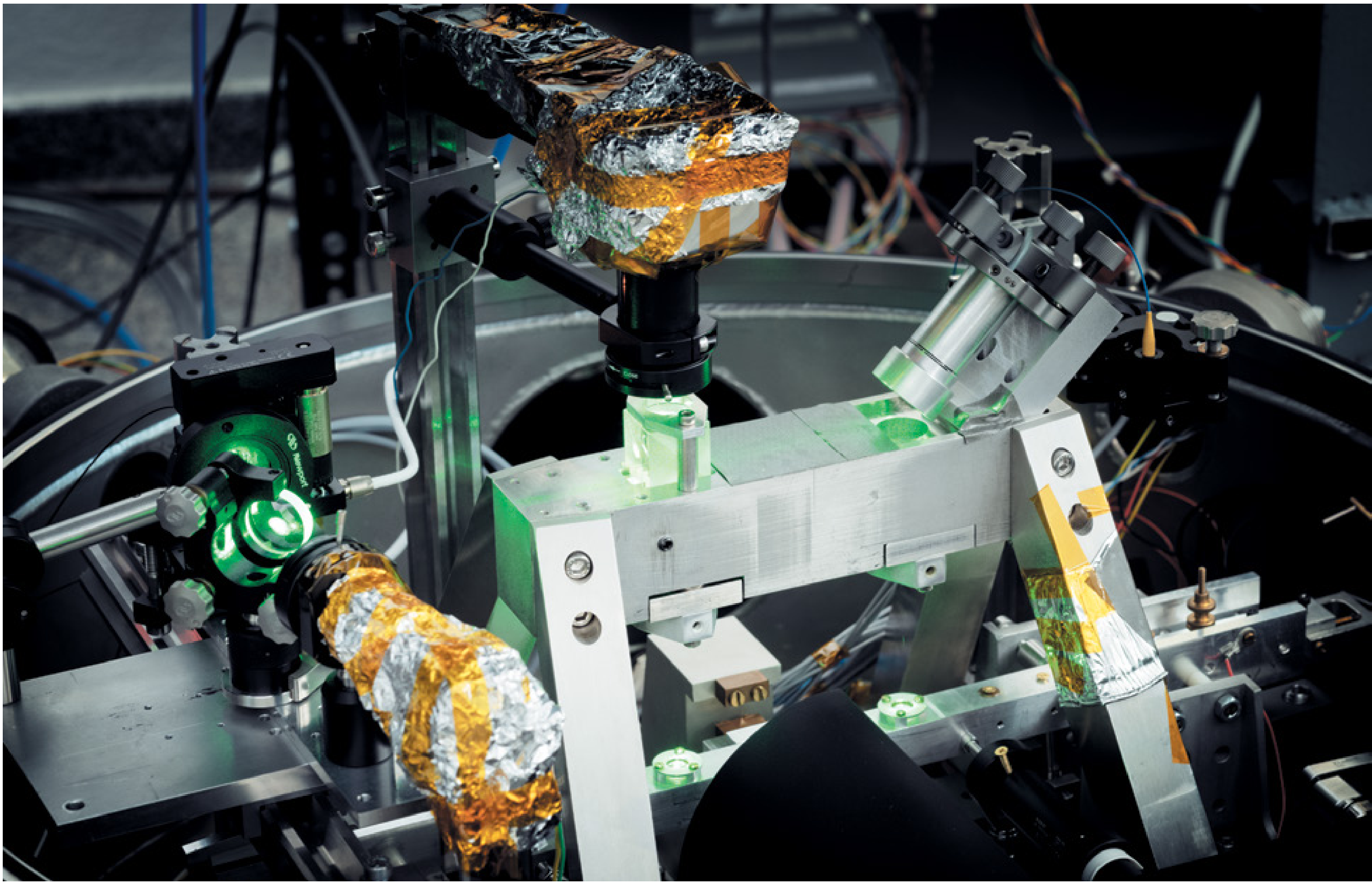


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CALLONI points to a beam that will tilt with respect to another beam if a signal appears.

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AN INTERFEROMETER will use lasers to measure any slight displacement in the beam balance.

which change the energy of the vacuum for a short time, have an effect on the shape and the development of our universe. When this connection first became clear, cosmologists hoped it would solve a major puzzle in their field: the value of the cosmological constant, another way of describing the energy in empty space.

THE COSMOLOGICAL CONSTANT

EINSTEIN PUBLISHED his general theory of relativity in 1915, but he soon realized he had a problem. The theory seemed to predict an expanding universe, yet astronomers at the time believed that our cosmos was static: that space had a fixed, unchanging size.

Three years after he published the theory, Einstein found that he could add a term called the cosmological constant to his equations without changing the fundamental laws of physics. Given the right value, this term would ensure that the universe neither expands nor contracts. In the 1920s, however, astronomer Edwin Hubble used the largest telescope of the time, the Hooker telescope at Mount Wilson Observatory in California, to observe that the farther away a galaxy was from Earth, the faster it seemed to be receding. This trend revealed that space was, in fact, expanding. Einstein discarded the cosmological constant, calling it "folly."

More than half a century later there was another twist: By observing distant supernovae, two research teams independently proved that the universe isn't just expanding—it's doing so at an accelerated rate. The force that pushes space apart has since been called dark energy. It acts as a kind of counterpart to gravity, preventing all massive objects from eventually collapsing into one place. According to theoretical predictions, dark energy accounts for about 68 percent of the total energy in space. At this point, the cosmological constant came back into fashion as a possible explanation for this mysterious form of energy. And the cosmological constant, in turn, is thought to get its energy from the vacuum.

At first, the scientific community was delighted: it seemed that general relativity's constant was the result of the energy of virtual particles in empty space. Two different fields of physics—relativity and quantum theory—were coming together to explain the accelerated expansion of the universe. But the joy didn't last long. When scientists did the two calculations, the energy of the vacuum based on quantum field theory turned out to be much larger—120 orders of magnitude higher—than the value of the cosmological constant astronomers derived from measuring the universe's expansion. The best way to resolve the discrepancy would be to measure the energy present in the vacuum directly—by weighing virtual particles.

A SCALE FOR THE UNIVERSE

IF THE VACUUM ENERGY derived from quantum theory is correct, then something must be stifling this energy's effects on the expansion of space. If this value were the true strength of dark energy, space would be ballooning much, much faster. If, on the other hand, the value from cosmology is right, then physicists are vastly overestimating how much energy virtual particles contribute to the vacuum.

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That vacuum fluctuations and virtual particles exist has been widely accepted at least since the Casimir effect was demonstrated. And quantum theory's predicted strength for the fluctuations can't be completely off, either, because laboratory experiments confirm the theory to great precision. But might it be possible that virtual particles don't actually gravitate the way we think and therefore don't affect the weight of space as we tend to expect?

So far no direct measurements have ever been made of how virtual particles behave with respect to gravity. And some scientists have suggested they may interact with gravity differently than ordinary matter does. For instance, in 1996 physicists Alexander Kaganovich and Eduardo Guendelman of Ben-Gurion University in Israel worked out a theoretical model in which the fluctuations of the vacuum have no gravitational effect. This might be the case if there are extra dimensions beyond the regular three of space and one of time that we're familiar with. These hidden dimensions might modify the behavior of gravity on very small scales.

Yet mass differences in atomic nuclei of elements such as aluminum and platinum can be explained only if certain quantum fluctuations contribute to their weight. That's why many physicists are convinced virtual particles interact with gravity just as ordinary particles do. "There are clear indications of this but so far no direct proof," says theoretical physicist Carlo Rovelli, who was involved in the Archimedes experiment's theoretical planning.

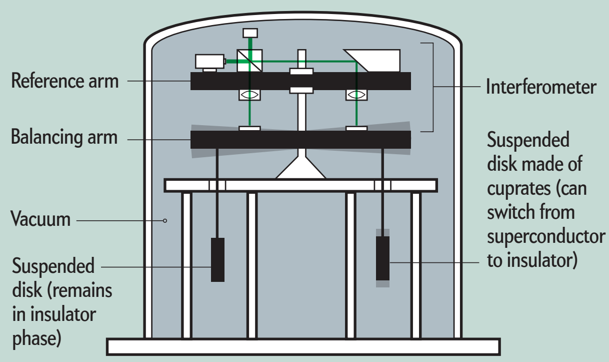
To verify that virtual particles interact with gravity like normal matter, the Archimedes team members want to use the Casimir effect to weigh virtual particles with a simple beam balance. The balance will sit inside their vacuum chamber, a cylindrical container of "nothing" that will be nested in several layers of insulation to keep it extremely cold and protected from the outside environment. Those layers, in turn, will sit deep inside the Sardinian cave, protecting the delicate apparatus from every possible influence of the aboveground world. These barriers are necessary because the scientists are searching for a minute signal: the slight movement of the balance when the Casimir effect turns on, changing the weight of a sample material by altering the population of virtual particles inside it. "In principle, we have known the basic principles needed for this for decades," explains postdoctoral researcher Luciano Errico, a member of the experiment team. "I wondered myself at first why it took so long to tackle this task."

In 1929 physicist Richard Tolman wondered if certain forms of energy (he focused on heat) could be weighed. Seven decades later Calloni thought about pushing the idea forward. After reading a technical paper by the late physicist Steven Weinberg, he envisioned weighing the gravitational contribution of virtual particles using Archimedes' principle, which states that when a body is immersed in fluid, it experiences an upward buoyant force equal to the weight of the fluid that the body displaces. If virtual particles have weight, then a cavity of metal plates in a vacuum should experience a buoyant force. The cavity is essentially displacing the regular vacuum, with its abundant virtual particles, with a lighter vacuum containing fewer virtual particles. Determining the strength of the buoyant force, which depends on the density of the virtual particles, will reveal their weight.

To measure this force within their vacuum tube, the researchers will suspend two samples made of different materials from a two-meter-tall, 1.50-meter-wide balance and induce the Casimir effect within one. To do this, they will heat both materials at regular intervals by about four degrees Celsius and then cool them down again. This temperature difference is sufficient for one of the samples to switch back and forth between a superconducting phase (when electricity flows freely within the material) and an insulating phase (when electricity cannot easily flow). The other material, however, always remains an insulator. As the conductivity changes in the first sample, it acts like the classic two-plate setup, and the number of possible virtual particles within it varies. Thus, the buoyancy force periodically increases and decreases on the first weight. This variation should cause the balance to oscillate at regular intervals, like a seesaw with two children sitting on it.

In planning the experiment, the scientists needed to find a suitable material that could be heated and cooled uniformly and quickly and that exhibited a strong Casimir effect. After considering several options, the team chose superconducting crystals called cuprates. The resulting samples are disks with a diameter of about 10 centimeters that are only several millimeters thick. To date, no one has proved that the Casimir effect works in high-temperature superconductors, but the scientists are betting that it does.

Archimedes Scheme



The researchers have rigged the balance so that it hangs freely in space within its vacuum chamber, which will cool the entire apparatus to less than 90 kelvins (just under –180 degrees Celsius). The chamber itself will be packed into two larger metal containers—one canister filled with liquid nitrogen, within another airless container, which acts like a thermos. Without that final cocoon, the second layer would heat up too quickly. The entire structure will be about three meters high, wide and deep and will weigh several tons.

A SENSITIVE SIGNAL

CALLONI BEGAN WORKING with colleagues in 2002 to develop a theoretical model to calculate the strength of the buoyancy force for different experimental setups. They found the force in a realistic experiment would be about 10^{-16} newton. Measuring such a tiny force is like trying to weigh the DNA in a cell. "The numbers are devastating," says physicist Ulf Leonhardt of the Weizmann Institute of Science in Rehovot, Israel. "On the other hand, 10 years ago hardly anyone believed gravitational waves could now be detected."

In fact, the technology in today's gravitational-wave detectors, which first observed their target in 2015, could help detect the tiny gravitational signals the Archimedes experiment seeks. Calloni himself was involved in building the Italian gravitational-

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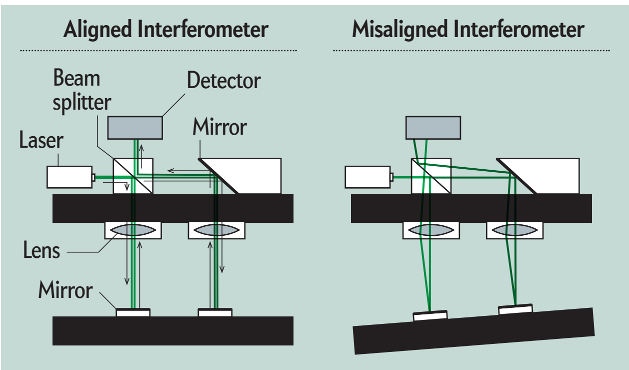


THE EXPERIMENT will be housed in an abandoned Sardinian mine.

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wave detector VIRGO. "It is only because of the extremely sensitive instruments made for precision measurements of gravitational waves that all this is possible," Errico says.

To be able to detect the minuscule deflections it seeks, the Archimedes experiment will use two laser systems that share some similarities with the laser-and-mirrors setups within gravitational-wave detectors. The first splits a laser beam in two by directing it through a beam splitter to both ends of the scale, where they are reflected by attached mirrors. The beams are then recombined by further mirrors and travel to a detector. If the beam is in balance, the two beams will travel exactly the same distance. If the arm is slightly tilted in one direction, the beams will cover different distances. In that case, the crests and troughs of the laser beam waves will meet in the measuring device in a staggered manner, producing a different intensity. This system can detect even the smallest deviations from equilibrium.



A second set of lasers measures the direction of the tilt if there is a large movement. A simplified prototype of the experiment that operates at room temperature was remarkably sensitive, boding well for the final Archimedes apparatus's performance. But even with such sophisticated measurement systems, implementing the experiment will be difficult. "In experiments like this, the whole world works against you," says physicist Vivishek Sudhir of the Massachusetts Institute of Technology.

To shield the balance from the outside world, the physicists needed a site with as little seismic activity as possible—hence Sardinia. The island has other advantages. It's not too densely populated, which keeps human-made noise low. It also has more than 250 abandoned mines, many of them no longer in use, which are appealing because there are even fewer vibrations underground and because the temperature inside a mine is especially stable.

Eventually the team fixed on the Sos Enattos mine on the east side of the island, which has been closed since the 1990s. The mine has a long history: in ancient times, the Romans used it to extract silver and zinc ores. Today Loddo, our driver for the trip, is responsible for the shafts; he had previously worked as a technician in the mine. "Just before it was closed, there were only about 30 people working there," Loddo says as he walks us through the mine. "They then took care of converting the underground passages so that they could be used as a museum." A few years later he took over the mine's management and organized guided tours. In some areas, there are still educational installations depicting the different steps miners took in their work: here a figure filling a cart with rocks, there someone attaching explosives to a wall, and elsewhere an elaborate replica of a worker operating a pneumatic drill. "Today the mine is used only for scientific operations," Loddo explains.

The room where they plan to do the experiment looks more like an archaeological site than a laboratory, with its high walls of unadorned stone and vaulted cave ceiling. "The whole room has already been enlarged quite a bit, but there is still a lot of work to be done," Calloni says. The room still has to get bigger, for example. It needs a ventilation shaft, a proper floor, and more.

The final version of the balance setup was recently completed and shipped to Sardinia. The vacuum chamber is at the test site, but its two outer envelopes are still in production. When they arrive and when the cave is ready, scientists will move the entire setup to this dark underground room and start running real trials.

It's been a long process to get to this point. "It took me about six months to plan the setup in detail," Errico says. "Where should which adjusting screw go? What does the ideal beam splitter look like, and where do you position it? It then took about a year for all the parts to arrive and for me to put it together." And the calibration to get the laser to hit all the fixtures accurately? "That actually only took 30 minutes. I had planned everything so precisely that there were only a few degrees of freedom. When everything really worked out the way I had imagined, I almost cried with joy."

PRECISION MEASUREMENTS

DESPITE THE TEAM'S careful planning, the measurement will be quite challenging, says Lamoreaux, who first demonstrated the Casimir effect. "I have long dreamed of measuring the Casimir force between superconducting plates," he says. "But making a suitable sample was beyond my capabilities."

The experiment's precision measurements would have to be a factor of 10 better than the best gravitational-wave detectors operating today, points out Karsten Danzmann, director of the Max Planck Institute for Gravitational Physics in Hannover, Germany. He finds the project fascinating but ambitious.

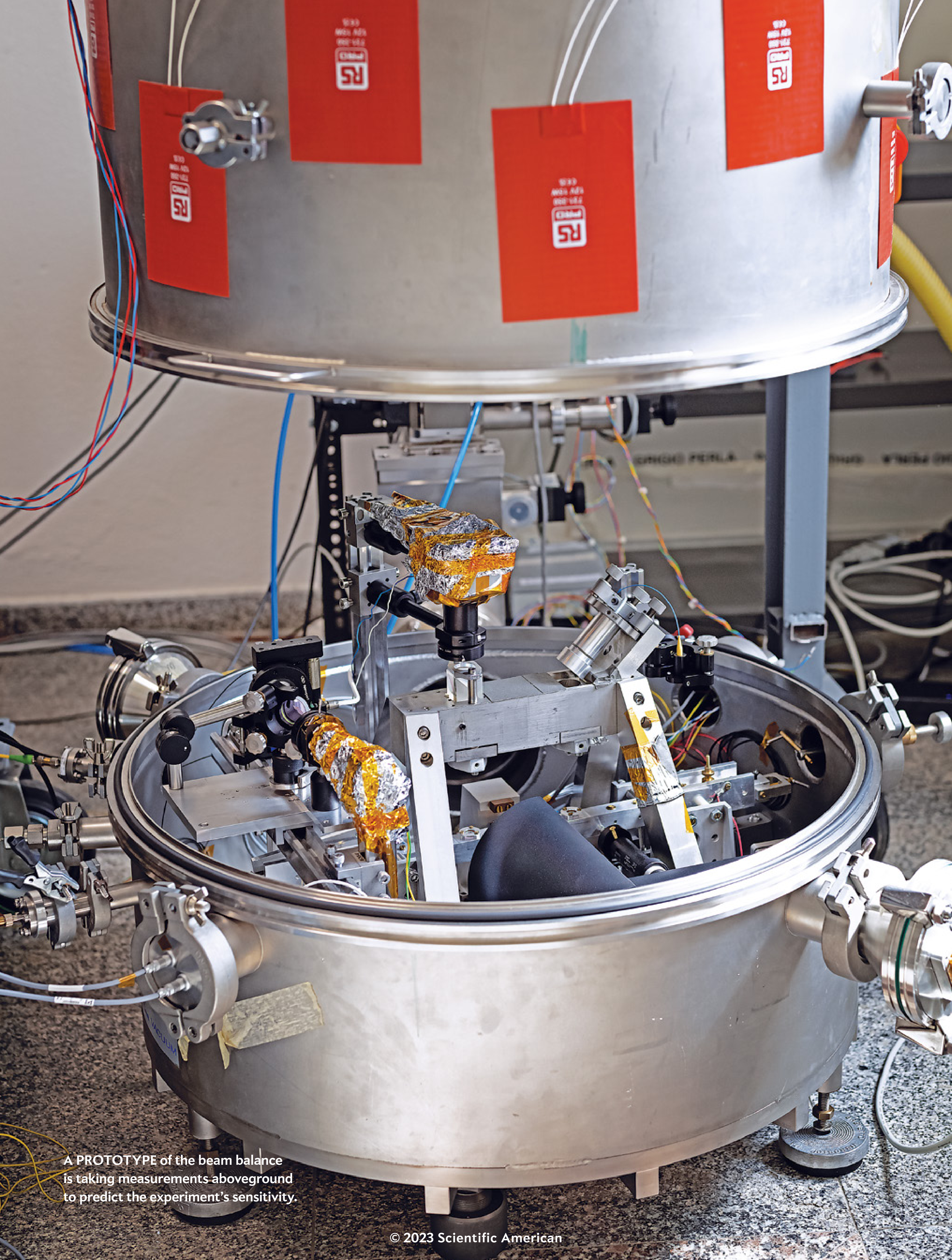
If it works, though, the results will have major consequences. "The experiment is extremely important," Leonhardt says, "because it would prove that vacuum fluctuations are indeed a real quantity with a gravitational contribution." If the measurements match expectations and show that virtual particles interact gravitationally just like ordinary matter, then we will know for sure that vacuum fluctuations must affect Einstein's general relativity equations. Consequently, they probably have very strong effects. In that case, cosmologists will have to explain what suppresses the influence of vacuum energy in the universe.

If the deflections of the balance turn out differently than expected, it might mean several things. On the one hand, such a result could open the door to entirely new physics if it showed that virtual particles don't gravitate. But "a missing signal could also be because there is no Casimir effect in cuprates, or it is very weak," says experimental physicist Markus Aspelmeyer of the University of Vienna. "Therefore, it is even more important to test separately from this experimentally."

The Archimedes researchers themselves aren't making any predictions. "We don't want to formulate a hypothesis yet, so as not to falsify the experiment," Calloni says. "But whatever result we get, it will definitely be exciting." SA

Manon Bischoff is a theoretical physicist and editor at *Spektrum,* a partner publication of *Scientific American.*

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A PROTOTYPE of the beam balance is taking measurements aboveground to predict the experiment's sensitivity.

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PARTICLES AND MATERIALS

Tricking Light

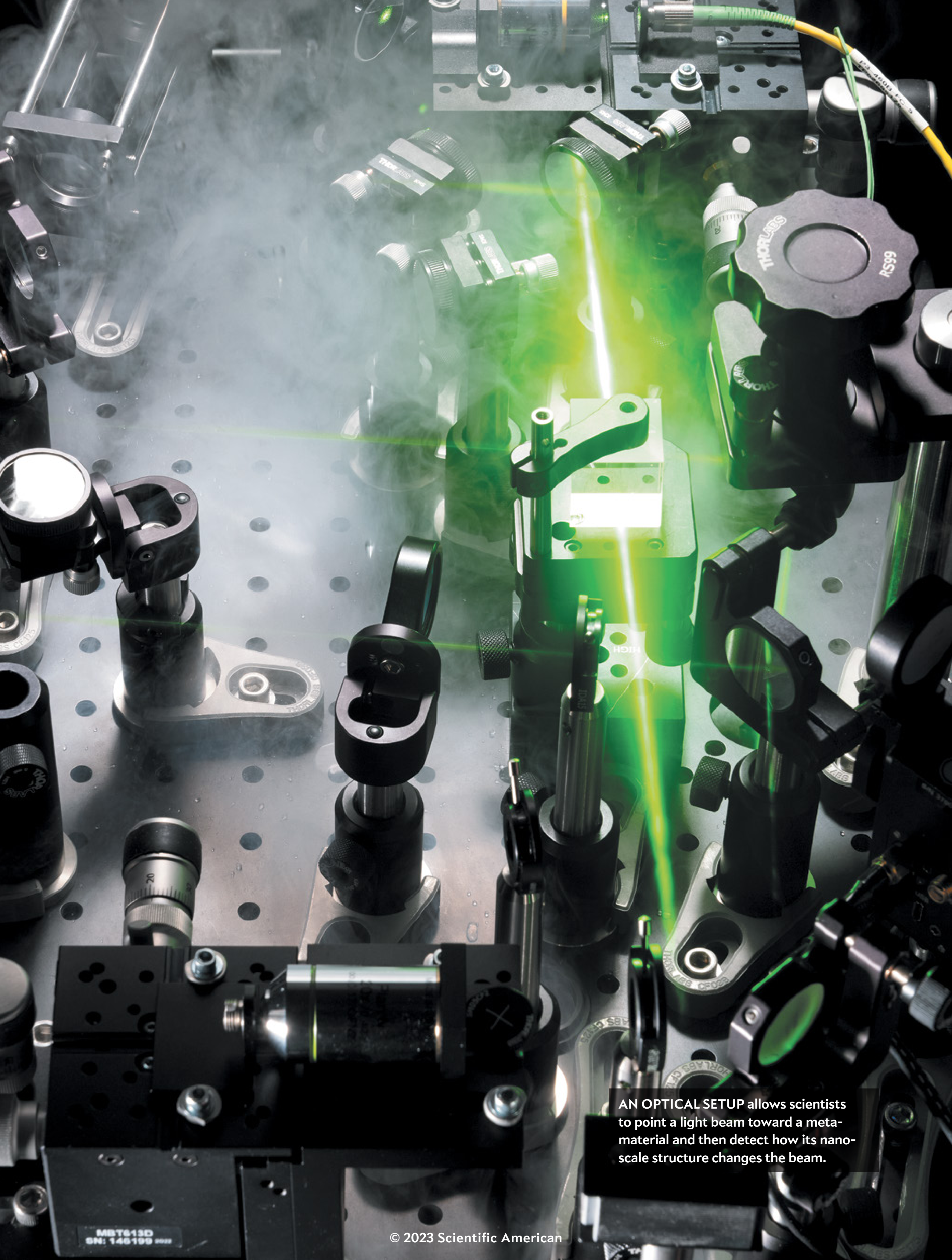
Newly invented metamaterials can modify waves, creating optical illusions and useful technologies

By Andrea Alù

Photographs by Craig Cutler



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AN OPTICAL SETUP allows scientists to point a light beam toward a metamaterial and then detect how its nanoscale structure changes the beam.

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WE ARE SURROUNDED BY WAVES. TINY VIBRATIONAL WAVES TRANSPORT sound to our ears. Light waves stimulate the retinas of our eyes. Electromagnetic waves bring radio, television and endless streaming content to our devices. Remarkably, all these different waves are governed largely by the same fundamental physical principles. And recently there has been a revolution in our ability to control these waves using materials, engineered at the nanoscale, known as metamaterials.

The Greek prefix *meta* means "beyond." These engineered materials let us move beyond the traditional ways in which waves and matter interact, creating technologies where light and sound appear to disobey conventional rules. The marquee example of this new style of materials is the "invisibility cloak"—a metamaterial coating that can hide an object in plain sight. Several research teams around the world, including mine, have designed and produced metamaterial coatings that can redirect light waves that hit them, effectively preventing light from bouncing off the object and reaching our eyes and even from leaving shadows. Although these inventions have limitations—they aren't quite the Harry Potter–style invisibility cloaks that many people imagine—they nonetheless interact with light in a way that seems like magic.

Cloaks are just one example of metamaterial technology. Other metamaterials allow light to travel one way but not the opposite—a valuable tool for communication and detection of objects—and to break symmetries of geometry and time. With modern nanofabrication tools and a better understanding of how light and matter interact, we can now structure metasurfaces to produce any pattern, color and optical feature we can think of.

BENDING AND TWISTING LIGHT

FOR CENTURIES scientists have strived to control the properties of light and sound as they interact with our sensory systems. An early success in this quest was the invention of stained glass: ancient Romans and Egyptians learned how to melt metallic salts into glass to tint it. The tiny metal nanoparticles dispersed in the glass absorb specific wavelengths and let others through, creating bright colors in masterpieces that we still admire today. In the 17th century Isaac Newton and Robert Hooke recognized that the hue and iridescence of some animals are created by nanoscale patterns on the surface of their body parts—another example of how nanostructured materials can create surprising optical effects.

Human eyes are excellent at detecting two fundamental properties of light: its intensity (brightness) and its wavelength—that is, its color. A third important property of light is its polarization, which describes the trajectory that light's electromagnetic fields trace in space over time. Although humans cannot distinguish one polarization from another with our eyes, several animal species have polarization sensitivity, allowing them to see more, better orient themselves in their surroundings and signal to other creatures.

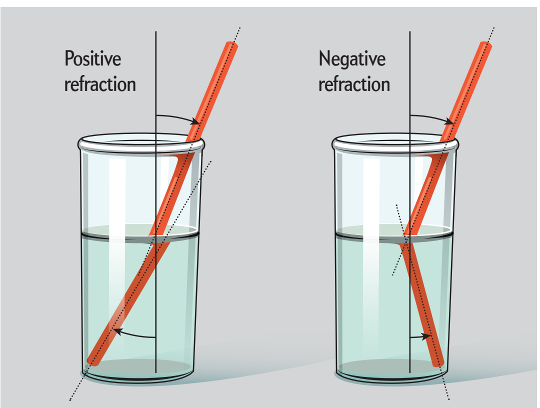
In the late 19th century, a few years after James Clerk Maxwell's discovery of the equations of electromagnetism, Jagadish Chandra Bose built the first examples of what we could call a metamaterial. By manually twisting jute fibers and arranging them in regular arrays, he demonstrated that linearly polarized electromagnetic waves—light whose electric and magnetic fields oscillate along straight lines—rotate their polarization as they propagate through and interact with the jute structures. Bose's twisted jute showed that it was possible to engineer an artificial material to control light in unprecedented ways.

The modern era of metamaterials can be traced back to 2000, when physicists David R. Smith of Duke University, the late Sheldon Schultz of the University

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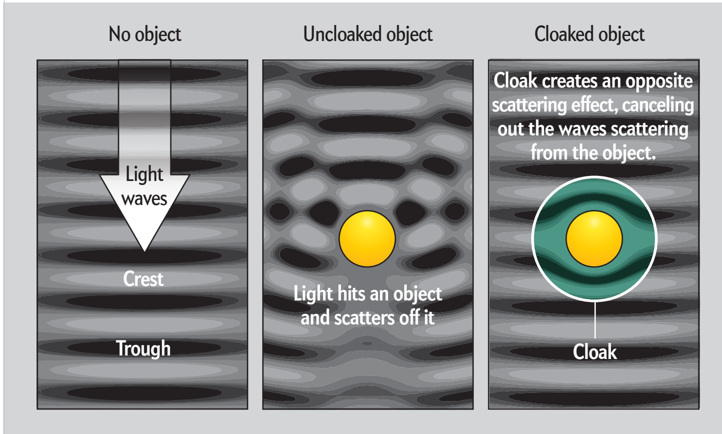
of California, San Diego, and their colleagues created an engineered material unlike any seen before—a material with a *negative* index of refraction. When a beam of light travels from one medium to another—from air to glass, say—its speed changes, causing the beam to bend, or "refract." The difference in index of refraction between the two materials defines the angle of that bending.

Refraction phenomena are the basis of most modern optical devices, including lenses and displays, and explain why a straw in a glass of water looks broken. For all known natural materials, the index of refraction is positive, meaning that light always bends on the same side of the interface, with a larger or smaller angle from the interface as a function of the change in index. Light entering a medium with a negative index of refraction, on the contrary, would bend backward, creating unexpected optical effects, such as a straw appearing to lean the wrong way. Scientists long assumed that it was impossible to find or create a material supporting negative refraction, and some argued that it would violate fundamental physical principles. When Schultz, Smith and their colleagues combined tiny copper rings and wires on stacked circuit-board substrates, however, they demonstrated that a microwave beam passing through this engineered material undergoes negative refraction. This striking advance showed that metamaterials can yield a much wider set of refractive indexes than nature offers, opening the door to totally new technological possibilities. Since then, researchers have created negative-index materials for a wide range of frequencies, including for visible light.



Cloaking

One of the biggest early successes of metamaterials is the invention of a coating that hides an object from view. Under normal circumstances, as light hits an object, its waves are disturbed and scattered, revealing the object's presence (*center*). A metamaterial cloak, however, causes the light bouncing off it to perfectly cancel the light reflected from the object underneath it, producing undisturbed light waves that conceal the object's presence (*right*).



CLOAKING TECHNOLOGIES

AFTER THIS INITIAL BREAKTHROUGH, a great deal of metamaterial research focused on cloaking. Nearly 20 years ago, while I was working with Nader Engheta of the University of Pennsylvania, we designed a metamaterial shell that would make an object undetectable by causing the light waves bouncing off the shell to cancel out the light waves scattered from the cloaked object. No matter which direction it came from, a wave that hit the structure would be redirected by the cloak in a way that canceled the wave scattered by the object itself. As a result, the cloaked object would be impossible to detect via external illumination: from an electromagnetic point of view, it would appear not to exist.

Around the same time, John B. Pendry of Imperial College London and Ulf Leonhardt, now at the Weizmann Institute of Science in Rehovot, Israel, proposed other interesting ways to use metamaterials to cloak objects. And within a few years various experimental demonstrations turned these proposals into reality. My group, for instance, produced a three-dimensional cloak that can drastically reduce the amount of radio waves that scatter off of a cylinder, making it difficult to detect via radar. Existing stealth technologies can hide objects from radar by absorbing the impinging waves, but metamaterial cloaks do much better because they don't just suppress the reflected waves—they reroute the incoming waves to eliminate scattering and shadows, making the cloaked object undetectable. We and other groups have extended cloaking to acoustic (sound) waves, creating objects that can't be detected by sonar devices. Other scientists have even made cloaks for thermal and seismic waves.

There is, however, a long way to go from these devices to invisibility cloaks like those pictured in movies, which allow the multiwavelength background behind an object to shine through. Our real-life cloaks are limited to either small sizes or narrow wavelengths of operation. The underlying challenge is the competition against the principle of causality: no

Graphics by Jen Christiansen

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information can travel faster than the speed of light in free space. It is impossible to fully restore the background electromagnetic fields as if they were traveling through the object without slowing them down.

Based on these principles, my group has demonstrated that we cannot *completely* suppress scattering from an object at more than a single wavelength (a single color of light) using a passive metamaterial coating. Even if we induce only partial transparency, we face a severe trade-off between how big the cloaked object can be and how many colors of light we can cloak it for. Cloaking a large object at visible wavelengths remains far-fetched, but we can use metamaterial cloaks for smaller objects and longer wavelengths, with exciting opportunities for radar, wireless communications and high-fidelity sensors that don't perturb their surroundings as they are operated. Cloaks for other kinds of waves, such as sound, have fewer limitations because these waves travel at much slower speeds.

SPATIAL SYMMETRIES

A PARTICULARLY POWERFUL TOOL for designing and applying metamaterials for various purposes is the concept of symmetry. Symmetries describe aspects of an object that do not change when it is flipped, rotated or otherwise transformed. They play a fundamental role in all natural phenomena. According to a 1915 theorem by mathematician Emmy Noether, any symmetry in a physical system leads to a conservation law. One example is the connection between temporal symmetry and energy conservation: if a physical system is described by laws that do not explicitly depend on time, its total energy must be preserved. Similarly, systems obeying spatial symmetries, such as periodic crystals that remain the same under translations or rotations, preserve some properties of light, such as its polarization. By breaking symmetries in controlled ways, we can design metamaterials to overcome and locally tailor these conservation laws, enabling novel forms of light control and transformation.

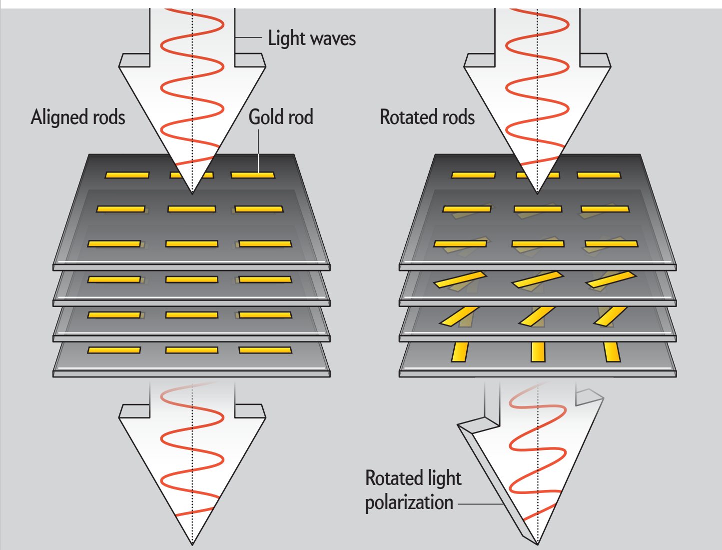
As an example of the powerful role of symmetries for metamaterial design, my group has engineered an optical metamaterial that can efficiently rotate the polarization of light that travels through it—in some ways, it is a nanoscale version of Bose's twisted jute arrangement. The material is made of multiple thin layers of glass, each one embedded with rows of gold rods, tens of nanometers long. First, we create one layer of nanorods all oriented in a certain direction over the glass. Then we stack a second layer, which looks identical to the first, except that we rotate all the rods at a specific angle. The next layer is adorned by nanorods further rotated by this same angle, and so on. Overall, the stack is only about a micron thick, yet it features a specific degree of broken spatial symmetry compared with natural periodic crystals, where molecules are all lined up in straight rows. As light passes through this thin metamaterial, it interacts with the gold nanorods and is slowed down by electron oscillations at their surface. The emerging light-matter interactions are controlled by the twisted symmetry of the crystal lattice, enabling a large rotation of the incoming light polarization over a broad range of wavelengths. This form of polarization control can benefit many technologies, such as liquid-crystal displays and sensing tools used in the pharmaceutical industry, which rely on polarization rotation that typically emerges much less efficiently in natural materials.

Underlying rotational symmetries also play a crucial role in governing other metamaterial responses. Pablo Jarillo-Herrero's group at the Massachusetts Institute of Technology recently showed that two closely spaced layers of graphene—just a single layer of atoms each—carefully rotated with respect to one another by a precise angle result in the striking emergence of superconductivity. This feature, which the two layers individually do not possess, allows electrons to flow along the material with zero resistance, all because of the broken symmetry induced by the twist. For a specific rotation angle, the emerging interactions between the neighboring atoms in the two layers define a totally new electronic response.

Inspired by this demonstration, in 2020 my group showed that a somewhat analogous phenomenon can occur not for electrons but for light. We used a stack of

Broken Symmetry

One way to alter how waves travel through a material is by breaking its usual symmetry. The author's group, for instance, created a metamaterial by layering sheets of glass with tiny gold nanorods embedded within them. In each layer, the rods are rotated by a specific angle, destroying the perfect symmetry between layers. The effect is that the material forces the polarization of light waves traveling through it to rotate—a useful trick for many modern technologies.



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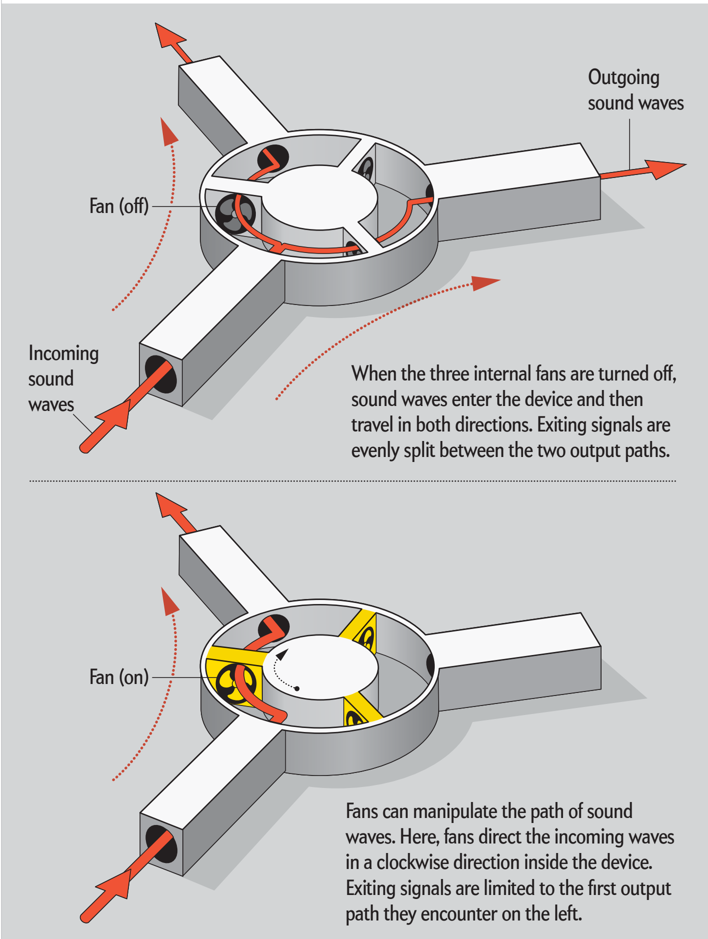


A METAMATERIAL undergoes testing in a chamber that enables very precise measurements of radio and millimeter-wavelength light.

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One-Way Sound

Another way to play with broken symmetry is with a device the author's group created in which sound can travel in only one direction. The structure consists of a circular aluminum cavity in which small fans spin air. Because of the Doppler effect, the cavity resonates at different frequencies for clockwise-traveling sound waves than for waves going the other way. The resulting interference lets sound through in just one direction.



Ultimately we can connect many of these devices to form a hexagonal lattice that supports robust one-way sound transport on its boundary.



two thin layers of molybdenum trioxide (MoO_3) and rotated one with respect to the other. Individually each layer is a periodic crystal lattice, in which the underlying molecules are arranged in a repeating pattern. When light enters this material, it can excite the molecules, causing them to vibrate. Certain wavelengths of light, when polarized in a direction aligned with the molecules, prompt strong lattice vibrations—a phenomenon called a phonon resonance. Yet light with the same wavelength and perpendicular polarization produces a much weaker material response because it does not drive these vibrations. We can take advantage of this strong asymmetry in the optical response by rotating one layer with respect to the second one. The twist angle once again controls and modifies the optical response of the bilayer in dramatic ways, making it very different from that of a single layer.

For example, light emitted by a molecule placed on the surface of a conventional material such as glass or silver flows outward in circular ripples, as when a stone hits the surface of a pond. But when our two MoO_3 layers are stacked on top of each other, changing the twist angle can drastically alter the optical response. For a specific twist angle between the crystal lattices, light is forced to travel in just one specific direction, without expanding in circular ripples—the analogue of superconductivity for photons. This phenomenon opens the possibility of creating nanoscale images beyond the resolution limits of conventional optical systems because it can transport the subwavelength details of an image without distortion, efficiently guiding light beyond the limits imposed by diffraction. Light in these materials is so strongly linked to material vibrations that the two form a single quasiparticle—a polariton—in which light and matter are strongly intertwined, offering an exciting platform for quantum technologies.

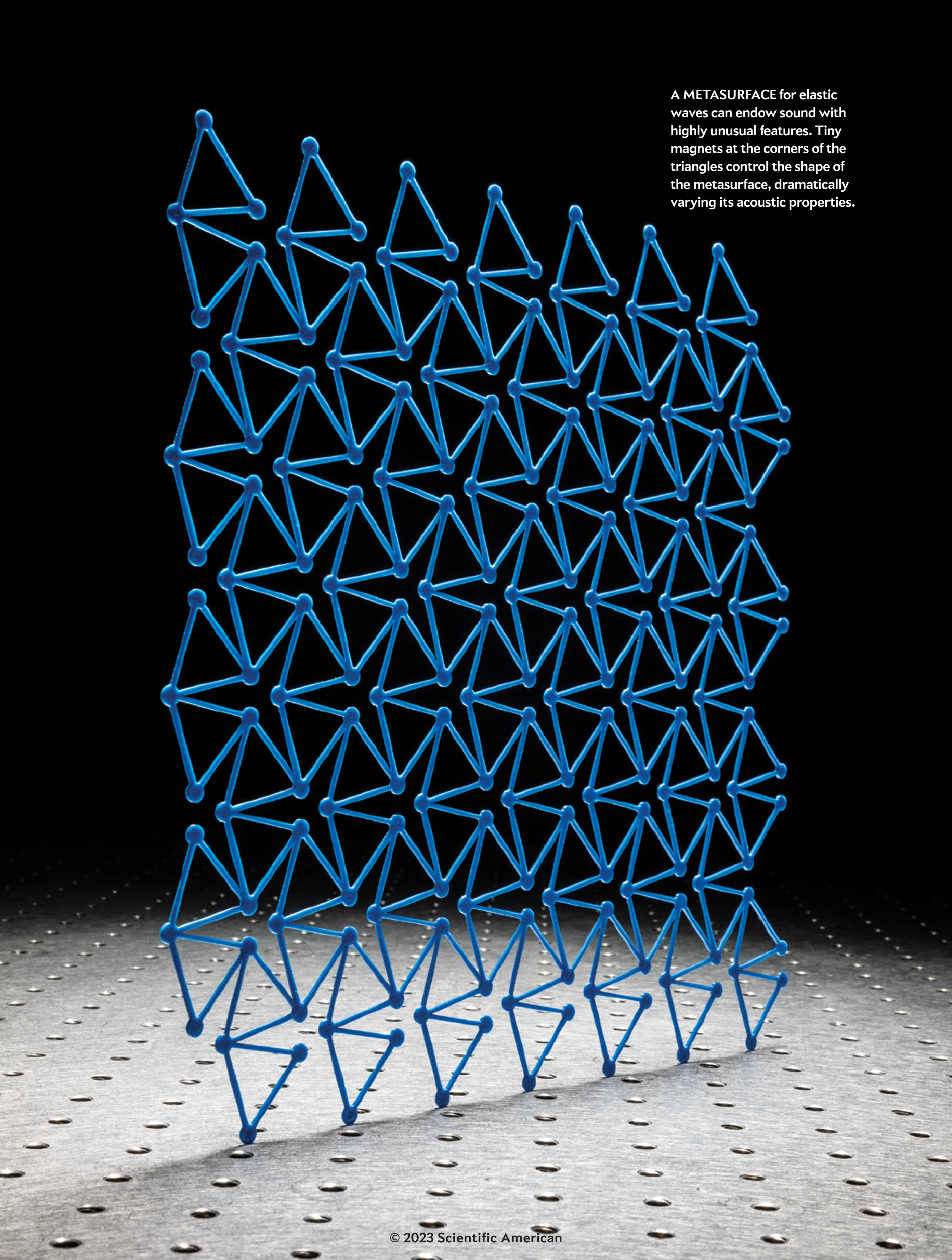
SYMMETRIES IN TIME

THE ROLE OF SYMMETRY in metamaterials is not limited to spatial symmetries, such as the kind broken by geometric rotations. Things get even more interesting when we experiment with breaking time-reversal symmetry.

The equations that govern wave phenomena are typically reversible in time: if a wave can travel from point A to point B, it can also travel back from B to A with the same features. Time-reversal symmetry explains the common expectation that if we can hear or see someone, they can also hear or see us. Breaking this symmetry in wave transmission—known as reciprocity—can be important for many applications. Nonreciprocal transmission of radio waves, for instance, can enable more efficient wireless communications in which signals can be transmitted and received at the same time without interference, and it can prevent contamination by the reflection of signals you send out. Nonreciprocity for light can protect sensitive laser-beam sources from unwanted reflections and provides the same benefit in radar and lidar technologies.

An established way to break this fundamental sym-

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A METASURFACE for elastic waves can endow sound with highly unusual features. Tiny magnets at the corners of the triangles control the shape of the metasurface, dramatically varying its acoustic properties.

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metry exploits magnetic phenomena. When a ferrite—a nonmetallic material with magnetic properties—is subject to a constant magnetic field, its molecules sustain tiny circulating currents that rotate with a handedness determined by the magnetic field orientation. In turn, these microscopic currents induce a phenomenon called Zeeman splitting: light waves with right-handed circular polarization (an electric field that rotates clockwise) interact with these molecules with a different energy than left-handed (counterclockwise) waves. The difference in energy is proportional to the applied magnetic field. When a linearly polarized wave travels through a magnetized ferrite, the overall effect is to rotate the polarization, in some ways similar to the metamaterials discussed earlier. The fundamental difference is that here the handedness of the polarization rotation is determined by the external magnetic bias, not by the broken symmetry in the metamaterial constituents. Hence, in these magnetized materials, light's polarization rotation has the same handedness when it's traveling in one direction as it does when it's moving in the opposite direction—a feature that violates reciprocity. Time-reversal symmetry is now broken.

We can exploit this phenomenon to engineer devices that allow waves to propagate in only one direction. Yet few natural materials possess the desired magnetic properties to achieve this effect, and those that do can be difficult to integrate into modern devices and technologies based on silicon. In recent years the metamaterials community has been working hard to create more efficient ways to break wave reciprocity without magnetic materials.

My group has shown that we can replace the tiny circulating currents in a magnetized ferrite with mechanically rotating elements in a metamaterial. We achieved this effect in a single compact acoustic device by using small computer fans spinning air inside a circular aluminum cavity, creating a first-of-its-kind nonreciprocal device for sound. When we turn on the fans, the frequencies at which the cavity resonates are different for counterrotating sound waves, similar to how Zeeman splitting changes the energy of light's interactions in a ferrite. As a result, a sound wave in this rotating cavity experiences a very different interaction depending on whether it travels clockwise or counterclockwise inside it.

We can then route sound waves nonreciprocally—one way only—through the device. Remarkably, the airflow speed necessary to create this effect is hundreds of times slower than the speed of the sound waves, making this technology quite simple to develop. Such compact nonreciprocal devices can then form the basis of a metamaterial, made by connecting these elements in a lattice. These engineered crystal lattices transport sound in highly unusual, nonreciprocal ways, reminiscent of how electrons travel with unique features in topological insulators.

Can we use a similar trick for light? In 2018 Tal Carmon's group at Tel Aviv University demonstrated an analogous effect by spinning the read-head of a hard-disk drive coupled to an optical fiber at kilohertz frequencies, demonstrating nonreciprocal transmission of light through it. The researchers' setup showed that mechanically rotating elements can be used to force light to travel through a device in one direction only. An arguably more practical route is to use metamaterials made of time-varying constituents that are switched on and off with specific patterns in space, mimicking rotation. Based on these principles, my group has created several technologies that operate efficiently as nonreciprocal devices. Their small footprints allow us to easily integrate them into larger electronic systems.

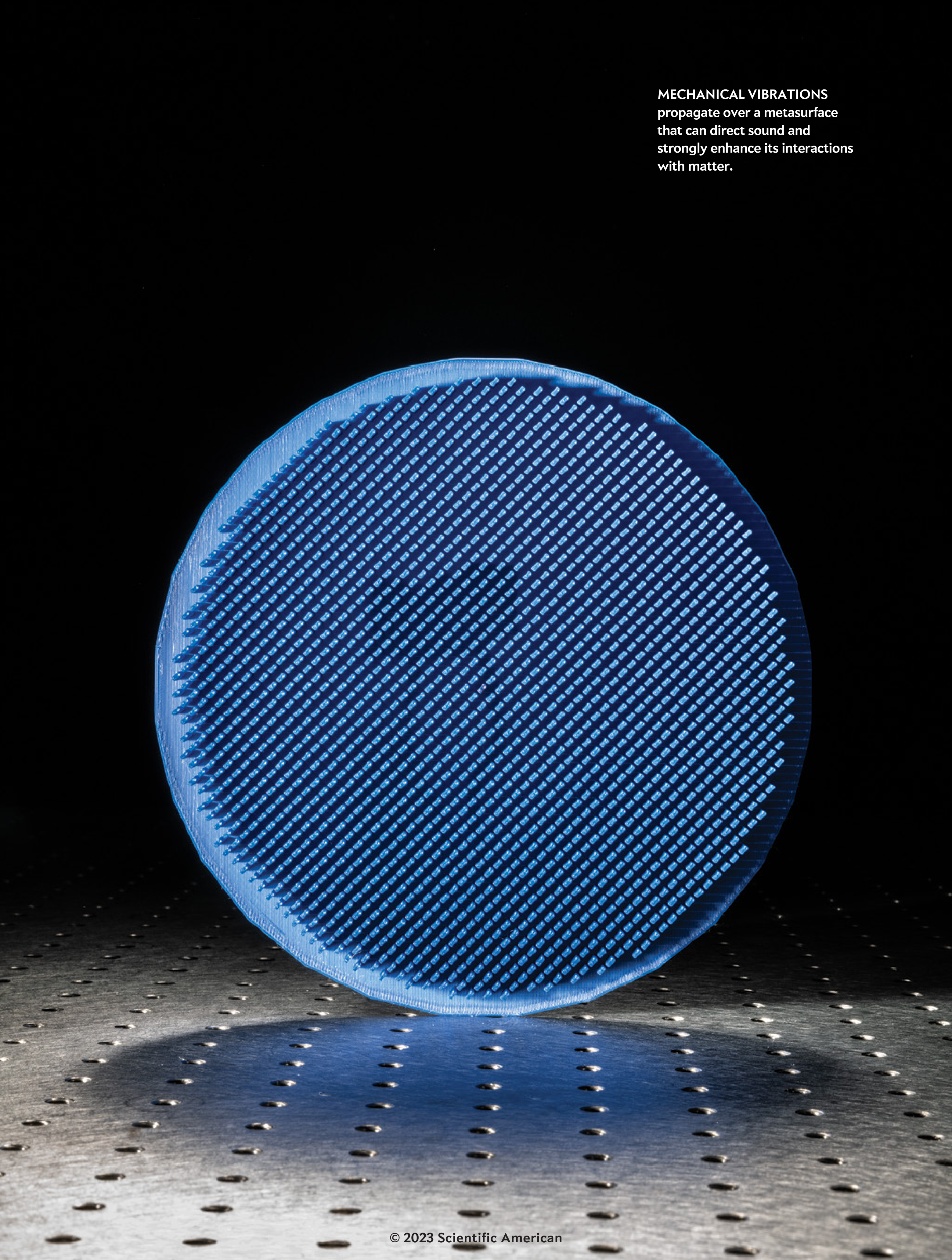
We have also extended these techniques to thermal emission, the radiation of light driven by heat. All hot bodies emit light, and a universal principle known as Kirchhoff's law of thermal radiation states that reciprocal materials in equilibrium must absorb and emit thermal radiation at the same rate. This symmetry introduces several limitations for device designs for thermal energy management and for energy-harvesting devices such as solar cells. By employing design principles similar to the ones described earlier to break light reciprocity, we are envisioning systems that do not obey the symmetry between absorption and emission. We can structure metamaterials to efficiently absorb heat without needing to reemit a portion of the absorbed energy toward the source, as a normal material would, enhancing the amount of energy we can harvest. Applied to static mechanics, analogous principles have also allowed us to create a 3-D-printed object that asymmetrically transmits an applied static mechanical force—a kind of one-way glove that can apply pressure without feeling the back action.

MANY MORE WONDERS

THE OPPORTUNITIES OFFERED by metamaterials and broken symmetries to manipulate and control waves do not end here. Scientists have been discovering new ways to trick light and sound—for instance, by combining broken geometric symmetries and temporal symmetries in novel ways. Metamaterials can be featured on the walls and windows of smart buildings to control and route electromagnetic waves at will. Nanostructured metasurfaces can shrink bulky optical setups into devices thinner than a human hair, enhancing imaging, sensing and energy-harvesting technologies. Acoustic and mechanical metamaterials can route and control sound with an unprecedented degree of control. We expect many more wonders, given the enormous opportunities that modern nanofabrication techniques, our improved understanding of light-matter interactions, and sophisticated materials science and engineering present us. SA

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MECHANICAL VIBRATIONS propagate over a metasurface that can direct sound and strongly enhance its interactions with matter.

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When Particles Break the Rules

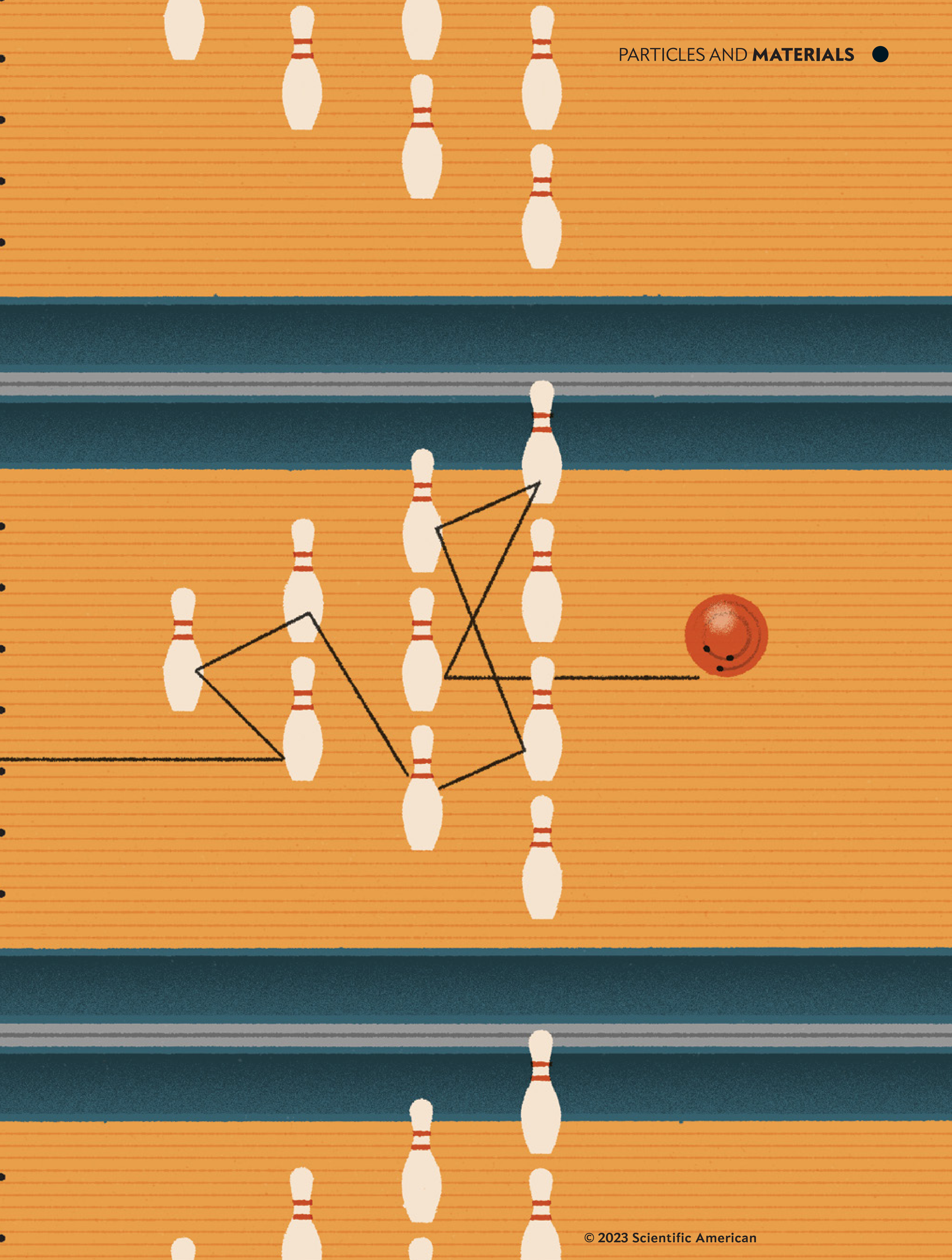


Hints of new particles and forces may be showing up at physics experiments around the world

By Andreas Crivellin

Illustration by Matt Harrison Clough

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BREAKING THE RULES IS EXCITING, ESPECIALLY if they have held for a long time. This is true not just in life but also in particle physics. Here the rule I'm thinking of is called "lepton flavor universality," and it is one of the predictions of our Standard Model of particle physics, which describes all the known fundamental particles and their interactions (except for gravity). For several decades after the invention of the Standard Model, particles seemed to obey this rule.

Things started to change in 2004, when the E821 experiment at Brookhaven National Laboratory on Long Island announced its measurement of a property of the muon—a heavy version of the electron—known as its g-factor. The measurement wasn't what the Standard Model predicted. Muons and electrons are both part of a class of particles called leptons (along with a third particle, the tau, as well as the three generations of neutrinos). The rule of lepton flavor universality says that because electrons and muons are charged leptons, they should all interact with other particles in the same way (barring small differences related to the Higgs particle). If they don't, then they violate lepton flavor universality—and the unexpected g-factor measurement suggested that's just what was happening.

If particles really were breaking this rule, that would be exciting in its own right and also because physicists believe that the Standard Model can't be the ultimate theory of nature. The theory doesn't explain why neutrinos have mass, nor what makes up the invisible dark matter that seems to dominate the cosmos, nor why matter won out over antimatter in the early universe. Therefore, the Standard Model must be merely an approximate description that we will need to supplement by adding new particles and interactions. Physicists have proposed a huge number of such extensions, but at most one of these theories can be correct, and so far none of them has received any direct confirmation. A measured violation of the Standard Model would be a flashlight pointing the way toward this higher theory we seek.

A TRIP TO ELBA

THE E821 EXPERIMENT and the discovery of mysterious muon behavior happened before my time in particle physics. I got involved in the business of lepton flavor universality violation about 10 years ago, as a postdoc in Bern, Switzerland, when I was invited to a meeting about the proposed SuperB collider to be built in Tor Vergata near Rome. The meeting was being held on the picturesque Italian island of Elba on the Tyrrhenian Sea. Though picturesque, the island is not easy to reach. The invitation was on short notice; I quickly booked a train to Pisa but missed the conference bus. Fortunately, two of the organizers offered to take me along in their car to Elba. This ride proved fortuitous.

As we drove through beautiful landscapes, we chatted about physics. One of the scientists, an experimentalist named Eugenio Paoloni, asked me what I thought about the new measurements of B meson decays by the BaBar experiment in California, which pointed toward a violation of lepton flavor universality. B mesons are particles containing a beauty quark, and they are some of physicists' favorite particles to study because they decay in a variety of ways that have the potential to reveal new secrets of physics. I hadn't heard about the BaBar result, probably because at the time it hadn't attracted much attention. But I quickly thought of a possible explanation for the measurement—a new Higgs boson, in addition to the conventional one we know of, could cause the phenomena seen at BaBar. My interest in the topic of lepton flavor universality violations was born.

The rest of the workshop was uneventful. After the first day, the focus was on the development of the collider, and as a theorist I didn't understand a word the experimentalists were saying. So I enjoyed Elba and worked on a paper about my Higgs boson idea, which I finished shortly after my return to Bern. The article got published, but unfortunately the SuperB project was canceled, and the reactions of my colleagues to the paper were not enthusiastic, to say the least: "A year from now there will be nothing left to explain by new physics" was a typical response, meaning that the measurement was probably a statistical fluke and the anomaly would disappear with more data.

For some time after the BaBar findings, there were no new results related to this question, and things grew quiet. But then, in 2013, the LHCb experiment at the Large Hadron Collider (LHC) at CERN near Geneva observed a deviation from the Standard Model prediction in a complicated quantity called P_5' ("P-five-prime") related to how B mesons decay. On the surface, this quantity is not related to lepton flavor universality, and I didn't find the measurement very exciting at first. My feelings changed a year later, however, when LHCb analyzed a ratio called R(K), which *is* a measure of lepton flavor universality violation. The experiment found a deviation

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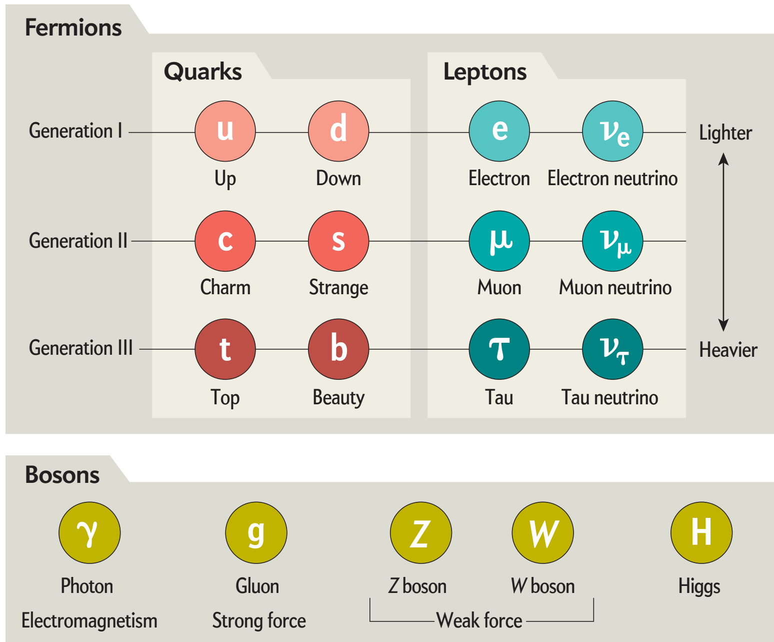
from the standard expectation, and it agreed with the P_5' findings, indicating that some new phenomenon might be occurring in muons.

A little while later the story hit a turning point, again at a conference. It was once more in Italy, this time in the charming village of La Thuile in the Alps, close to Mont Blanc. During the afternoon session after the skiing break, a partial eclipse of the sun took place. Just as amazing, scientists from LHCb announced a result that confirmed the previous P_5' measurement with more statistics—and my theory friends Joaquim Matias (called Quim) and David Straub agreed on the interpretation of these data. They had never agreed before. After thanking the speakers, I said to the audience, “Today we witnessed a rare event, a partial eclipse of the sun; however, that Quim and David agree for the first time is even more remarkable.”

From then on, the evidence for lepton flavor universality violation has continued to grow. Lepton universality is an old rule, and it has been many years since we last saw a part of the Standard Model be disproved. If the rule has truly been broken, there must be new interactions and new particles in the universe that we don’t know about—potentially particles that could help solve some of the biggest mysteries of our time.

The Standard Model

The known particles in the universe include fermions and bosons. Fermions are the building blocks of matter (including electrons and the quarks that form protons and neutrons). Each type of fermion comes in three varieties, called generations, that differ only in mass. Bosons carry the fundamental forces of nature. These forces shouldn’t treat fermions of subsequent generations differently.



BACK TO BASICS

TO FULLY UNDERSTAND lepton flavor universality and what violating it means, we first have to review the known constituents of matter at the subatomic scale and the interactions among them—that is, the Standard Model. The building blocks of matter are called fermions, after the great physicist Enrico Fermi. These matter particles come in three versions, called generations, that are the same in every way except for their mass. For instance, the electron has heavier versions called muons and taus, the up quark has heavier relatives named charm and top quarks, and the down quark is followed by strange and beauty quarks. Only the light flavors are stable—they constitute the ordinary matter our world is made of. (Two up quarks and a down quark make a proton, and one up quark and two down quarks make a neutron.)

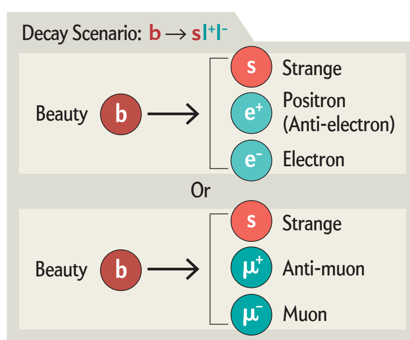
In addition to these particles, there are three forces through which the fermions can interact: the weak force, the strong force and the electromagnetic force (gravity is disregarded in the Standard Model because it is extremely weak at the subatomic scale). The corresponding force particles are called the *W* and *Z* bosons (for the weak force), gluons (for the strong force) and photons (for the electromagnetic force). Crucially, none of these interactions distinguishes among the three generations of fermions. The only thing that differentiates between the flavors is the famous Higgs boson, which is responsible for the fermions’ differing masses.

Or so we thought. If leptons are not universal—if there are forces that do discriminate among the generations—then something interesting is afoot. We have four different indications that lepton flavor universality might not hold true.

$b \rightarrow sl^+l^-$

THE FIRST COMES FROM MEASUREMENTS of a particle decay process labeled $b \rightarrow sl^+l^-$, where the b represents a beauty quark, s is a strange quark and l is a charged lepton (either an electron or a muon). During this process the beauty quark turns into a strange quark and produces a pair of leptons—specifically, a lepton and its antimatter partner. We would expect these classes of decays to give rise to muons approximately as often as electrons. Yet experiments that have measured these processes, such as LHCb, observe more electrons than muons, suggesting an imbalance. The combined experimental data now indicate that there is at most a 0.0001 percent chance this difference is only a statistical fluke.

Theorists have proposed various new



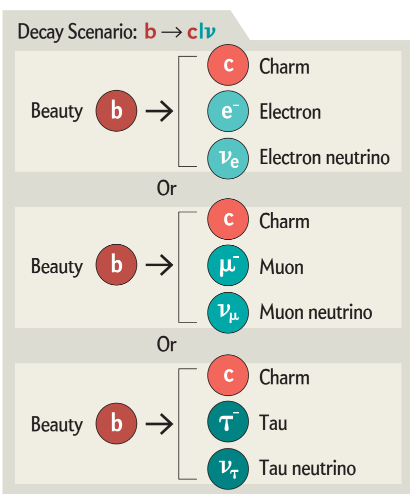
Graphics by Jen Christiansen

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particles and forces that can describe the data better than the Standard Model. How, one might ask, can one account for a lack of muons by adding new particles? Explaining a deficit through an addition might seem contradictory, but this would be the case only in classical physics. In the quantum realm, it makes perfect sense. Because all particles also have wave properties, quantum mechanics predicts so-called virtual particles that appear and disappear all the time in empty space. These particles can interfere with the decay processes of regular particles, causing the decay rates to change from what the Standard Model predicts. One possibility here, for instance, is that the beauty quark, on its way to turning into its usual decay products, briefly interacts with a virtual heavy version, a new *Z* boson (called *Z′*) that, contrary to the standard *Z* particle, does distinguish between muons and electrons.

$b \to c l \nu$

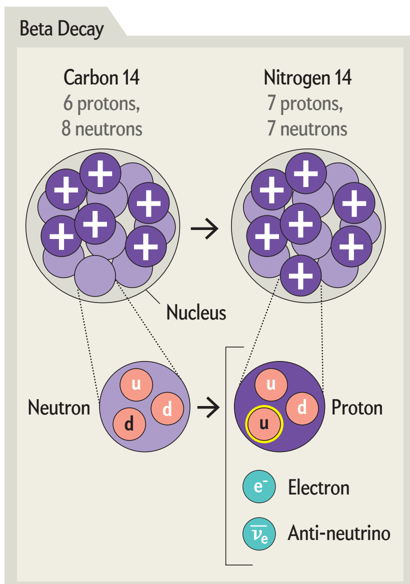
THE SECOND PIECE OF EVIDENCE for lepton universality violations comes from observing a beauty quark decaying into a charm quark (c), a lepton (l) and a neutrino (ν). Here tau leptons are expected less frequently than muons or electrons because they are heavier. Yet experiments such as BaBar, LHCb and an experiment in Japan called Belle have found that decays to tau particles happen more often than expected. Furthermore, the decays to muons and electrons show a relative asymmetry not expected in the Standard Model. Again, virtual particles may be interfering with the usual decay pathways. For instance, the beauty quark may interact with a virtual charged Higgs particle



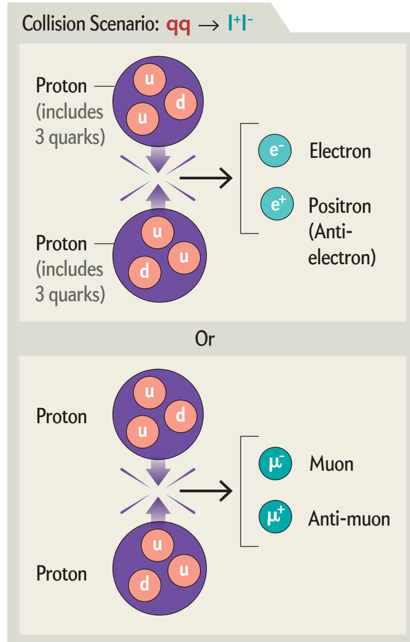
such as the one I proposed in 2012 (although this model now has some problems) or with another proposed novel particle referred to as a leptoquark.

CABIBBO ANGLE ANOMALY AND $qq \to e^+e^-$

ANOTHER INTRIGUING SIGNAL comes from certain radioactive decays called nuclear beta decays. Experiments have observed that these decays happen less frequently than expected. Beta decays occur within atomic nuclei, when down quarks transform into up quarks, or vice versa, allowing a neutron to become a proton, or the reverse, by emitting an electron and an antineutrino, or a positron (the antimatter counterpart of the electron) and a neutrino. When physicists combined their measurements with improved theoretical calculations, they realized that the particles within nuclei live longer than expected. This finding, called the Cabibbo Angle Anomaly, can be interpreted as another sign that electrons and muons might behave differently.



Furthermore, the CMS experiment at the LHC observed collisions of two protons that resulted in high-energy electrons ($qq \to e^+e^-$) and found that more electrons were produced in comparison to muons than expected, again pointing toward the violation of lepton flavor universality. This measurement and the Cabibbo Angle Anomaly could be related because the same interaction might suppress radioactive decays but also enhance the production of high-energy electrons.



THE MAGNETIC MOMENT OF THE MUON

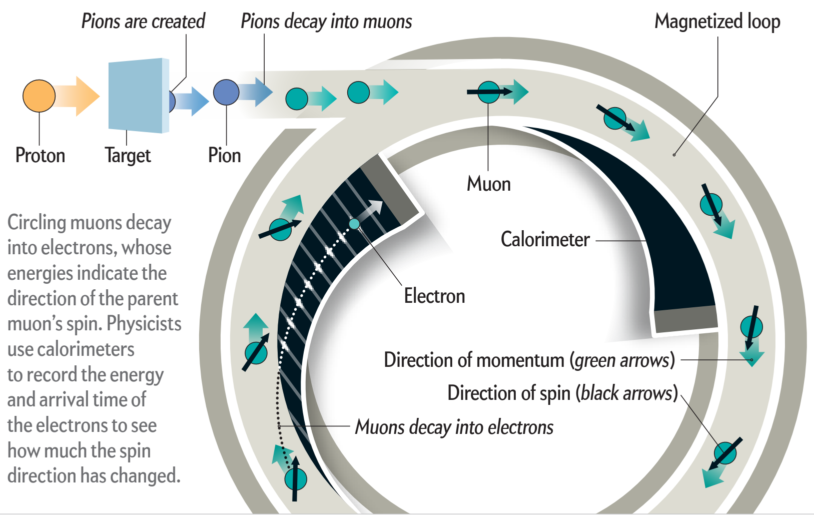
THIS TERM DESCRIBES how strongly a muon interacts with a magnetic field. Physicists quantify it with a g-factor, which we can predict very precisely with the Standard Model. Yet the Brookhaven experiment and results coming from the G-2 experiment at Fermilab deviate from this prediction. The G-2 project sends muons around a magnetized ring and measures how their spins change as they travel. If muons were alone in the experiment, their spins would not change—but virtual particles arising around them can tug on the muons, introducing a wobble to their spins. Of course, the known particles can appear as virtual particles to cause this effect, but the Standard Model calculation accounts for that. If there are more particles in nature than the ones we are aware of, however, the experiment will see an extra wobble—and it does.

The combined results from the G-2 experiment and the previous trial at Brookhaven add up to a probability of less than 0.01 percent that this anomaly is a statistical fluke. Yet the Standard Model prediction that enables this calculation is itself questionable. It is based on other experimental results (for example, from BaBar and the KLOE project in Italy) that do not agree with simulations of quantum-field theory that were recently performed on supercomputers.

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The G-2 Experiment

Some of the most intriguing signs that particles are breaking the rules of physics are measurements of muons, the heavier cousins of electrons. The G-2 experiment at Fermi National Accelerator Laboratory in Batavia, Ill., recently measured how muons' spins change as they circle within a magnetic field, and it came up with a different value than predicted. One interpretation is that novel, undiscovered particles are interfering with the muons' spin, adding an extra wobble.



A NEW PARTICLE ZOO

IF WE MUST EXTEND the Standard Model to account for these anomalies, how should we do it? In other words, how can we modify the equations describing nature so that theory and experiment agree?

Particles in one promising class that are capable of explaining these measurements are called leptoquarks. They connect a single quark directly to a single lepton: for instance, a lepton could transform into a quark by emitting a leptoquark—unlike any interaction in the Standard Model. Such a particle would be something radically new. It has been proposed in the past in the context of grand unified theories, which were devised to unite the different forces in the Standard Model at high energies. These high energies, however, would correspond to particles that are very heavy. Physicists would need to alter existing grand unified models to create a leptoquark light enough to affect the measurements we have discussed.

Another option involves other new particles, such as heavy fermions, heavy "scalar" particles (including new Higgs bosons), or novel gauge bosons (similar to the *W* and *Z* bosons). One intriguing way to predict such particles is by using theories that contain, in addition to our four dimensions (three of space and one of time), at least one extra dimension, compactly folded up and hidden within the ones we know.

Although these hints we have for new phenomena are very intriguing—at least in my view—it's critical that we corroborate these hints with additional, more precise data and more accurate theoretical calculations. A number of experiments and theoretical collaborations worldwide are working on this challenge. These include the LHCb experiment, which started collecting new data when the LHC began its most recent run in summer 2022. The Belle II experiment in Japan, which is dedicated to investigating B meson decays, is also gathering new evidence. If just one of these anomalies were confirmed, it would prove the existence of new particles or interactions. Furthermore, it would mean that the new particles must have masses that could be probed directly at the LHC or a future collider. These novel particles would also affect other phenomena we can observe, allowing physicists to make complementary tests of the new particles' properties.

Future accelerators could provide further insights. An electron-positron collider, such as the Future Circular Collider (FCC-ee) planned at CERN or the Circular Electron Positron Collider (CEPC) to be built in China, should have a sufficiently high luminosity (meaning it produces enough collisions) to create large numbers of *Z* bosons. These are useful for observing predicted deviations from the Standard Model in several ways. First, most anomalies, in particular the anomalous magnetic moment of the muon, would affect *Z* decays, such as *Z* bosons turning into a muon and an antimatter muon. Second, the *Z* bosons expected at the FCC-ee would produce an unprecedented number of beauty quarks and tau leptons. Large numbers of these particles would allow for precise tests of the decay processes for which we expect to see effects from new particles—effects that are currently not detectable because we lack enough data to see a strong signal.

An electron-positron collider could start operating around 2040. Later, physicists hope to collide protons in the same tunnel (the machine would then be called the FCC-hh), producing much higher energies and potentially creating the particles directly. Such a collider would probably not open before 2060, however. I would need a very healthy lifestyle to see one of the models I've worked on confirmed.

We are at an exciting point in this exploration. Results are constantly being updated and questioned. Recently new theory calculations bolstered the case for new physics in $b \to s l^+ l^-$ and $b \to c l \nu$ decays; meanwhile there have been rumors about the reliability of the corresponding experimental measurements. We are all eagerly awaiting updated measurements and further improved theoretical predictions. If the present hints of lepton universality violation hold up, they could provide long-sought guidance toward a more complete fundamental theory of particle physics. We hope such a theory will finally resolve some of our biggest questions about nature—neutrino masses, dark matter and the missing antimatter in our universe. SA

Andreas Crivellin is a theoretical physicist at the University of Zurich and the Paul Scherrer Institute in Switzerland.

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CRYSTALS IN TIME

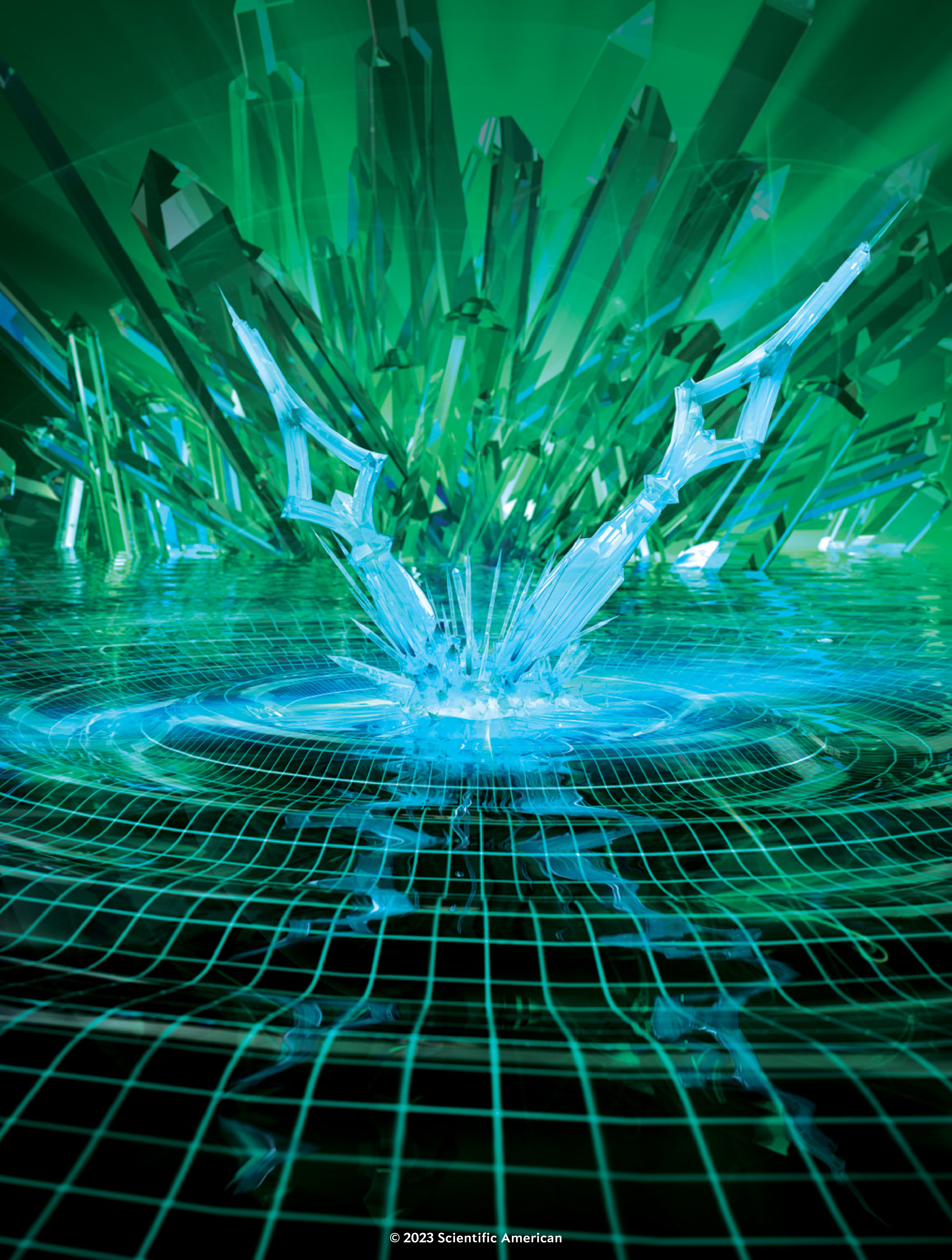
Surprising new states of matter called time crystals show the same symmetry properties in time that ordinary crystals do in space

By Frank Wilczek

Illustration by Mark Ross Studio



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CRYSTALS are nature's most orderly substances. Inside them, atoms and molecules are arranged in regular, repeating structures, giving rise to solids that are stable and rigid—and often beautiful to behold.

People have found crystals fascinating and attractive since before the dawn of modern science, often prizing them as jewels. In the 19th century scientists' quest to classify forms of crystals and understand their effect on light catalyzed important progress in mathematics and physics. Then, in the 20th century, study of the fundamental quantum mechanics of electrons in crystals led directly to modern semiconductor electronics and eventually to smartphones and the Internet.

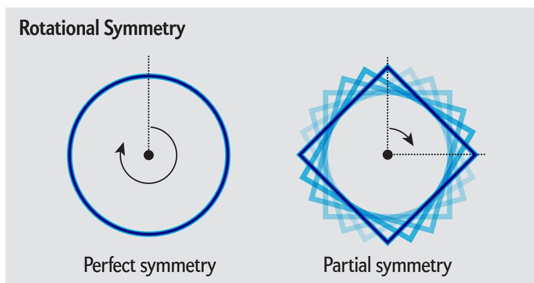
The next step in our understanding of crystals is occurring now, thanks to a principle that arose from Albert Einstein's relativity theory: space and time are intimately connected and ultimately on the same footing. Thus, it is natural to wonder whether any objects display properties in time that are analogous to the properties of ordinary crystals in space. In exploring that question, we discovered "time crystals." This concept, along with the growing class of novel materials that fit within it, has led to exciting insights about physics, as well as the potential for new applications, including clocks more accurate than any that exist now.

SYMMETRY

BEFORE I FULLY EXPLAIN this idea, I must clarify what, exactly, a crystal is. The most fruitful answer for scientific purposes brings in two profound concepts: symmetry and spontaneous symmetry breaking.

In common usage, "symmetry" very broadly indicates balance, harmony or even justice. In physics and mathematics, the meaning is more precise. We say that an object is symmetric or has symmetry if there are transformations that could change it but do not.

That definition might seem strange and abstract at first, so let us focus on a simple example: Consider a circle. When we rotate a circle around its center, through any angle, it remains visually the same, even though every point on it may have moved—it has perfect rotational symmetry. A square has some symmetry but less than a circle because you must rotate a square through a full 90 degrees before it regains its initial appearance. These examples show that the mathematical concept of symmetry captures an essential aspect of its common meaning while adding the virtue of precision.



A second virtue of this concept of symmetry is that it can be generalized. We can adapt the idea so that it applies not just to shapes but more widely to physical laws. We say a law has symmetry if we can change the context in which the law is applied without changing the law itself. For example, the basic axiom of special relativity is that the same physical laws apply when we view the world from different platforms that move at constant velocities relative to one another. Thus, relativity demands that physical laws display a kind of symmetry—namely, symmetry under the platform-changing transformations that physicists call "boosts."

A different class of transformations is important for crystals, including time crystals. They are the very simple yet profoundly important transformations known as translations. Whereas relativity says the

Graphics by Jen Christiansen

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same laws apply for observers on moving platforms, spatial translation symmetry says the same laws apply for observers on platforms in different places. If you move—or "translate"—your laboratory from one place to another, you will find that the same laws hold in the new place. Spatial translation symmetry, in other words, asserts that the laws we discover *anywhere* apply *everywhere*.

Time translation symmetry expresses a similar idea but for time instead of space. It says the same laws we operate under now also apply for observers in the past or in the future. In other words, the laws we discover at any time apply at every time. In view of its basic importance, time translation symmetry deserves to have a less forbidding name, with fewer than seven syllables. Here I will call it tau, denoted by the Greek symbol τ.

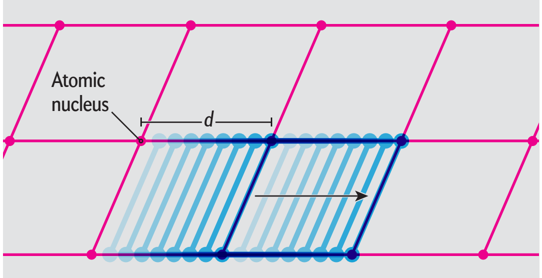
Without space and time translation symmetry, experiments carried out in different places and at different times would not be reproducible. In their everyday work, scientists take those symmetries for granted. Indeed, science as we know it would be impossible without them. But it is important to emphasize that we can test space and time translation symmetry empirically. Specifically, we can observe behavior in distant astronomical objects. Such objects are situated, obviously, in different places, and thanks to the finite speed of light we can observe in the present how they behaved in the past. Astronomers have determined, in great detail and with high accuracy, that the same laws do in fact apply.

SYMMETRY BREAKING

FOR ALL THEIR AESTHETIC SYMMETRY, it is actually the way crystals lack symmetry that is, for physicists, their defining characteristic.

Consider a drastically idealized crystal. It will be one-dimensional, and its atomic nuclei will be located at regular intervals along a line, separated by the distance d. (Their coordinates therefore will be nd, where n is a whole number.) If we translate this crystal to the right by a tiny distance, it will not look like the same object. Only after we translate through the specific distance d will we see the same crystal. Thus, our idealized crystal has a reduced degree of spatial translation symmetry, similarly to how a square has a reduced degree of rotational symmetry.

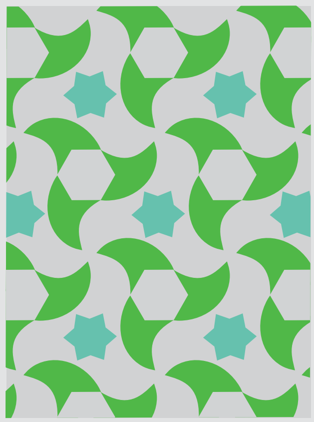
Translational Symmetry



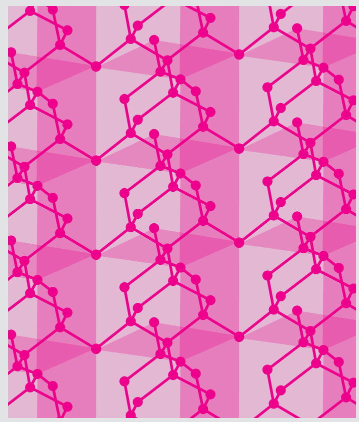
Physicists say that in a crystal the translational symmetry of the fundamental laws is "broken," leading to a lesser translational symmetry. That remaining symmetry conveys the essence of our crystal. Indeed, if we know that a crystal's symmetry involves translations through multiples of the distance d, then we know where to place its atoms relative to one another.

Crystalline patterns in two and three dimensions can be more complicated, and they come in many varieties. They can display partial rotational and partial translational symmetry. The 14th-century artists who decorated the Alhambra palace in Granada, Spain, discovered many possible forms of two-dimensional crystals by intuition and experimentation, and mathematicians in the 19th century classified the possible forms of three-dimensional crystals.

Complex Crystalline Pattern Examples



Two dimensions (from the Alhambra palace)



Three dimensions (diamond crystal structure)

In the summer of 2011 I was preparing to teach this elegant chapter of mathematics as part of a course on the uses of symmetry in physics. I always try to take a fresh look at material I will be teaching and, if possible, add something new. It occurred to me then that one could extend the classification of possible crystalline patterns in three-dimensional space to crystalline patterns in four-dimensional spacetime.

When I mentioned this mathematical line of investigation to Alfred Shapere, my former student turned valued colleague, who is now at the University of Kentucky, he urged me to consider two very basic physical questions. They launched me on a surprising scientific adventure:

What real-world systems could crystals in spacetime describe?

Might these patterns lead us to identify distinctive states of matter?

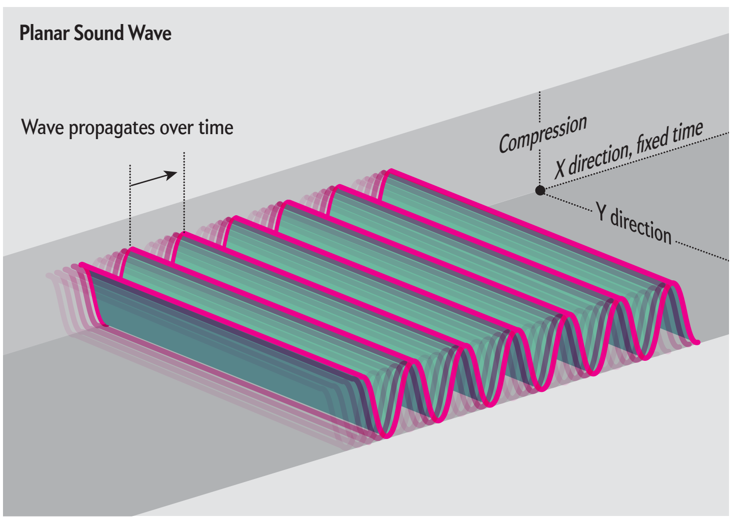
The answer to the first question is fairly straightforward. Whereas ordinary crystals are orderly arrangements of objects in space, spacetime crystals are orderly arrangements of events in spacetime.

As we did for ordinary crystals, we can get our

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bearings by considering the one-dimensional case, in which spacetime crystals simplify to purely time crystals. We are looking, then, for systems whose overall state repeats itself at regular intervals. Such systems are almost embarrassingly familiar. For example, Earth repeats its orientation in space at daily intervals, and the Earth-sun system repeats its configuration at yearly intervals. Inventors and scientists have, over many decades, developed systems that repeat their arrangements at increasingly accurate intervals for use as clocks. Pendulum and spring clocks were superseded by clocks based on vibrating (traditional) crystals, and those were eventually superseded by clocks based on vibrating atoms. Atomic clocks have achieved extraordinary accuracy, but there are important reasons to improve them further—and time crystals might help, as we will see later.

Some familiar real-world systems also embody higher-dimensional spacetime crystal patterns. For example, the pattern shown here can represent a planar sound wave, where the height of the surface indicates compression as a function of position and time. More elaborate spacetime crystal patterns might be difficult to come by in nature, but they could be interesting targets for artists and engineers—imagine a dynamic Alhambra on steroids.



These types of spacetime crystals, though, simply repackage known phenomena under a different label. We can move into genuinely new territory in physics by considering Shapere's second question. To do that, we must now bring in the idea of *spontaneous* symmetry breaking.

SPONTANEOUS SYMMETRY BREAKING

WHEN A LIQUID or gas cools into a crystal, something fundamentally remarkable occurs: the emergent solution of the laws of physics—the crystal—displays less symmetry than the laws themselves. As this reduction of symmetry is brought on just by a decrease in temperature, without any special outside intervention, we can say that in forming a crystal the material breaks spatial translation symmetry "spontaneously."

An important feature of crystallization is a sharp change in the system's behavior or, in technical language, a sharp phase transition. Above a certain critical temperature (which depends on the system's chemical composition and the ambient pressure), we have a liquid; below it we have a crystal—objects with quite different properties. The transition occurs predictably and is accompanied by the emission of energy (in the form of heat). The fact that a small change in ambient conditions causes a substance to reorganize into a qualitatively distinct material is no less remarkable for being, in the case of water and ice, very familiar.

The rigidity of crystals is another emergent property that distinguishes them from liquids and gases. From a microscopic perspective, rigidity arises because the organized pattern of atoms in a crystal persists over long distances and the crystal resists attempts to disrupt that pattern.

The three features of crystallization that we have just discussed—reduced symmetry, sharp phase transition and rigidity—are deeply related. The basic principle underlying all three is that atoms "want" to form patterns with favorable energy. Different choices of pattern—in the jargon, different phases—can win out under different conditions (for instance, various pressures and temperatures). When conditions change, we often see sharp phase transitions. And because pattern formation requires collective action on the part of the atoms, the winning choice will be enforced over the entire material, which will snap back into its previous state if the chosen pattern is disturbed.

Because spontaneous symmetry breaking unites such a nice package of ideas and powerful implications, I felt it was important to explore the possibility that τ can be broken spontaneously. As I was writing up this idea, I explained it to my wife, Betsy Devine: "It's like a crystal but in time." Drawn in by my excitement, she was curious: "What are you calling it?" "Spontaneous breaking of time translation symmetry," I said. "No way," she countered. "Call it time crystals." Which, naturally, I did. In 2012 I published two papers, one co-authored by Shapere, introducing the concept. A time crystal, then, is a system in which τ is spontaneously broken.

One might wonder why it took so long for the concepts of τ and spontaneous symmetry breaking to come together, given that separately they have been understood for many years. It is because τ differs from other symmetries in a crucial way that makes the question of its possible spontaneous breaking much subtler. The difference arises because of a profound theorem proved by mathematician Emmy Noether in 1915. Noether's theorem makes a connec-

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tion between symmetry principles and conservation laws—it shows that for every form of symmetry, there is a corresponding quantity that is conserved. In the application relevant here, Noether's theorem states that τ is basically equivalent to the conservation of energy. Conversely, when a system breaks τ, energy is not conserved, and it ceases to be a useful characteristic of that system. (More precisely: without τ, you can no longer obtain an energylike, time-independent quantity by summing up contributions from the system's parts.)

The usual explanation for why spontaneous symmetry breaking occurs is that it can be favorable energetically. If the lowest-energy state breaks *spatial* symmetry and the energy of the system is conserved, then the broken symmetry state, once entered, will persist. That is how scientists account for ordinary crystallization, for example.

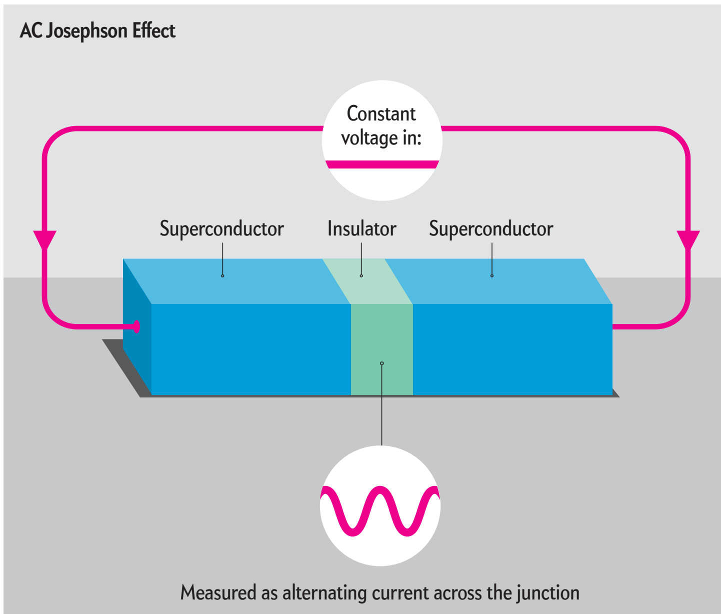
But that energy-based explanation will not work for τ breaking, because τ breaking removes the applicable measure of energy. This apparent difficulty put the possibility of spontaneous τ breaking, and the associated concept of time crystals, beyond the conceptual horizon of most physicists.

There is, however, a more general road to spontaneous symmetry breaking, which also applies to τ breaking. Rather than spontaneously reorganizing to a lower-energy state, a material might reorganize to a state that is more stable for other reasons. For instance, ordered patterns that extend over large stretches of space or time and involve many particles are difficult to unravel because most disrupting forces act on small, local scales. Thus, a material might achieve greater stability by taking on a new pattern that occurs over a larger scale than in its previous state.

Ultimately, of course, no ordinary state of matter can maintain itself against all disruptions. Consider, for example, diamonds. A legendary ad campaign popularized the slogan "a diamond is forever." But in the right atmosphere, if the temperature is hot enough, a diamond will burn into inglorious ash. More basically, diamonds are not a stable state of carbon at ordinary temperatures and atmospheric pressure. They are created at much higher pressures and, once formed, will survive for a very long time at ordinary pressures. But physicists calculate that if you wait long enough, your diamond will turn into graphite. Even less likely, but still possible, a quantum fluctuation can turn your diamond into a tiny black hole. It is also possible that the decay of a diamond's protons will slowly erode it. In practice, what we mean by a "state of matter" (such as diamond) is an organization of a substance that has a useful degree of stability against a significant range of external changes.

OLD AND NEW TIME CRYSTALS

THE AC JOSEPHSON EFFECT is one of the gems of physics, and it supplies the prototype for one large family of time crystals. It occurs when we apply a constant voltage V (a difference in potential energy) across an insulating junction separating two superconducting materials (a so-called Josephson junction, named after physicist Brian Josephson). In this situation, one observes that an alternating current at frequency $2eV/\hbar$ flows across the junction, where e is the charge of an electron and $\hbar$ is the reduced Planck's constant. Here, although the physical setup does not vary in time (in other words, it respects τ), the resulting behavior does vary in time. Full time translation symmetry has been reduced to symmetry under time translation by multiples of the period $\hbar/2eV$. Thus, the AC Josephson effect embodies the most basic concept of a time crystal. In some respects, however, it is not ideal. To maintain the voltage, one must somehow close the circuit and supply a battery. But AC circuits tend to dissipate heat, and batteries run down. Moreover, oscillating currents tend to radiate electromagnetic waves. For all these reasons, Josephson junctions are not ideally stable.



By using refinements such as fully superconducting circuits, excellent capacitors in place of ordinary batteries and enclosures to trap radiation, it is possible to substantially reduce the levels of those effects. And other systems that involve superfluids or magnets in place of superconductors exhibit analogous effects while minimizing those problems. Nikolay Prokof'ev and Boris Svistunov have proposed extremely clean examples involving two interpenetrating superfluids.

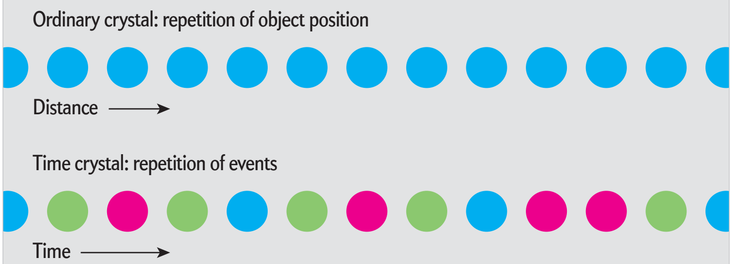
Thinking explicitly about τ breaking has focused attention on these issues and led to the discovery of new examples and fruitful experiments. Still, because the central physical idea is already implicit in Josephson's work of 1962, it seems appropriate to refer to all these as "old" time crystals.

"New" time crystals arrived with the March 9, 2017,

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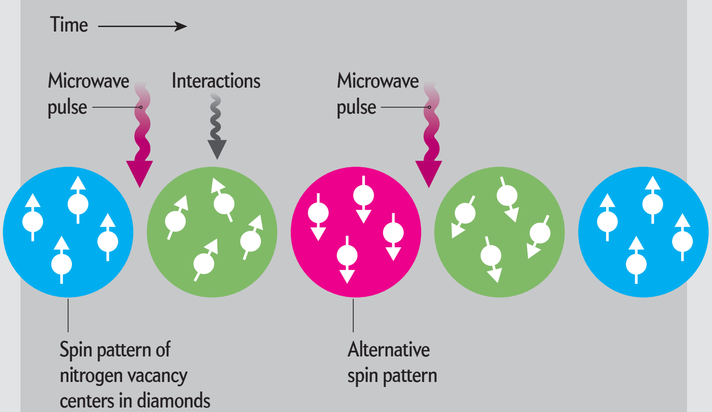
Making a Time Crystal

Just as the atoms in regular crystals repeat their arrangements over certain distances, time crystals are states of matter that repeat over specific periods. The first new materials that fit into this category were discovered in 2017 by two research teams, one led by Mikhail Lukin of Harvard University and the other by Christopher Monroe of the University of Maryland, College Park.



The Lukin Experiment

Lukin's group created a time crystal by manipulating the spins of atoms in so-called nitrogen vacancy centers—impurities in a diamond lattice. The researchers periodically exposed the diamond to laser pulses. Between pulses, the spins continued to interact with one another. The entire system repeated its overall configuration periodically—but not with the same period as the microwave pulses. Rather the system took on its own timing period, cycling at a fraction of the frequency of the pulses.



issue of *Nature,* which featured gorgeous (metaphorical) time crystals on the cover and announced "Time crystals: First observations of exotic new state of matter." Inside were two independent discovery papers. In one experiment, a group led by Christopher Monroe of the University of Maryland, College Park, created a time crystal in an engineered system of a chain of ytterbium ions. In the other, Mikhail Lukin's group at Harvard University realized a time crystal in a system of many thousands of defects, called nitrogen vacancy centers, in a diamond.

In both systems, the spin direction of the atoms (either the ytterbium ions or the diamond defects) changes with regularity, and the atoms periodically come back into their original configurations. In Monroe's experiment, researchers used lasers to flip the ions' spins and to correlate the spins into connected, "entangled" states. As a result, though, the ions' spins began to oscillate at only half the rate of the laser pulses. In Lukin's project, the scientists used microwave pulses to flip the diamond defects' spins. They observed time crystals with twice and three times the pulse spacing. In all these experiments, the materials received external stimulation—lasers or microwave pulses—but they displayed a different period than that of their stimuli. In other words, they broke time symmetry spontaneously.

These experiments inaugurated a direction in materials physics that has grown into a minor industry. More materials utilizing the same general principles—which have come to be called Floquet time crystals—have come on the scene since then, and many more are being investigated.

Floquet time crystals are distinct in important ways from related phenomena discovered much earlier. Notably, in 1831 Michael Faraday found that when he shook a pool of mercury vertically with period *T,* the resulting flow often displayed period 2*T.* But the symmetry breaking in Faraday's system—and in many other systems studied in the intervening years prior to 2017—does not allow a clean separation between the material and the drive (in this case, the act of shaking), and it does not display the hallmarks of spontaneous symmetry breaking. The drive never ceases to pump energy (or, more accurately, entropy), which is radiated as heat, into the material.

In effect, the entire system consisting of material plus drive—whose behavior, as noted, cannot be cleanly separated—simply has less symmetry than the drive considered separately. In the 2017 systems, in contrast, after a brief settling-down period, the material falls into a steady state in which it no longer exchanges energy or entropy with the drive. The difference is subtle but physically crucial. The new Floquet time crystals represent distinct phases of matter, and they display the hallmarks of spontaneous symmetry breaking, whereas the earlier examples, though extremely interesting in their own right, do not.

Likewise, Earth's rotation and its revolution around the sun are not time crystals in this sense. Their impressive degree of stability is enforced by the approximate conservation of energy and angular momentum. They do not have the lowest possible values of those quantities, so the preceding energetic argument for stability does not apply; they also do not involve long-range patterns. But precisely because of the enormous value of energy and angular momentum in these systems, it takes either a big disturbance or small disturbances acting over a long time to significantly change them. Indeed, effects that include the tides, the gravitational influence of other planets and

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even the evolution of the sun do slightly alter those astronomical systems. The associated measures of time such as "day" and "year" are, notoriously, subject to occasional correction.

In contrast, these new time crystals display strong rigidity and stability in their patterns—a feature that offers a way of dividing up time very accurately, which could be the key to advanced clocks. Modern atomic clocks are marvels of accuracy, but they lack the guaranteed long-term stability of time crystals. More accurate, less cumbersome clocks based on these emerging states of matter could empower exquisite measurements of distances and times, with applications from improved GPS to new ways of detecting underground caves and mineral deposits through their influence on gravity or even gravitational waves. DARPA—the Defense Advanced Research Projects Agency—has funded research on time crystals with such possibilities in mind.

THE TAO OF τ

THE CIRCLE OF IDEAS and experiments around time crystals and spontaneous τ breaking represents a subject in its infancy. There are many open questions and fronts for growth. One ongoing task is to expand the census of physical time crystals to include larger and more convenient examples and to embody a wider variety of spacetime patterns, by both designing new time crystal materials and discovering them in nature. Physicists are also interested in studying and understanding the phase transitions that bring matter into and out of these states.

Another task is to examine in detail the physical properties of time crystals (and spacetime crystals, in which space symmetry and τ are both spontaneously broken). Here the example of semiconductor crystals, mentioned earlier, is inspiring. What discoveries will emerge as we study how time crystals modify the behavior of electrons and light moving within them?

Having opened our minds to the possibility of states of matter that involve time, we can consider not only time crystals but also time quasicrystals (materials that are very ordered yet lack repeating patterns), time liquids (materials in which the density of events in time is constant but the period is not) and time glasses (which have a pattern that looks perfectly rigid but actually shows small deviations). Researchers are actively exploring these and other possibilities. Indeed, some forms of time quasicrystals and a kind of time liquid have been identified already.

So far we have considered phases of matter that put τ into play. Let me conclude with two brief comments about τ in cosmology and in black holes.

The steady-state-universe model was a principled attempt to maintain τ in cosmology. In that model, popular in the mid-20th century, astronomers postulated that the state, or appearance, of the universe on large scales is independent of time—in other words, it upholds time symmetry. Although the universe is always expanding, the steady-state model postulated that matter is continuously being created, allowing the average density of the cosmos to stay constant. But the steady-state model did not survive the test of time. Instead astronomers have accumulated overwhelming evidence that the universe was a very different place 13.7 billion years ago, in the immediate aftermath of the big bang, even though the same physical laws applied. In that sense, τ is (perhaps spontaneously) broken by the universe as a whole. Some cosmologists have also suggested that ours is a cyclic universe or that the universe went through a phase of rapid oscillation. These speculations—which, to date, remain just that—bring us close to the circle of ideas around time crystals.

It occurred to me that one could extend the classification of possible crystalline patterns in three-dimensional space to crystalline patterns in four-dimensional spacetime.

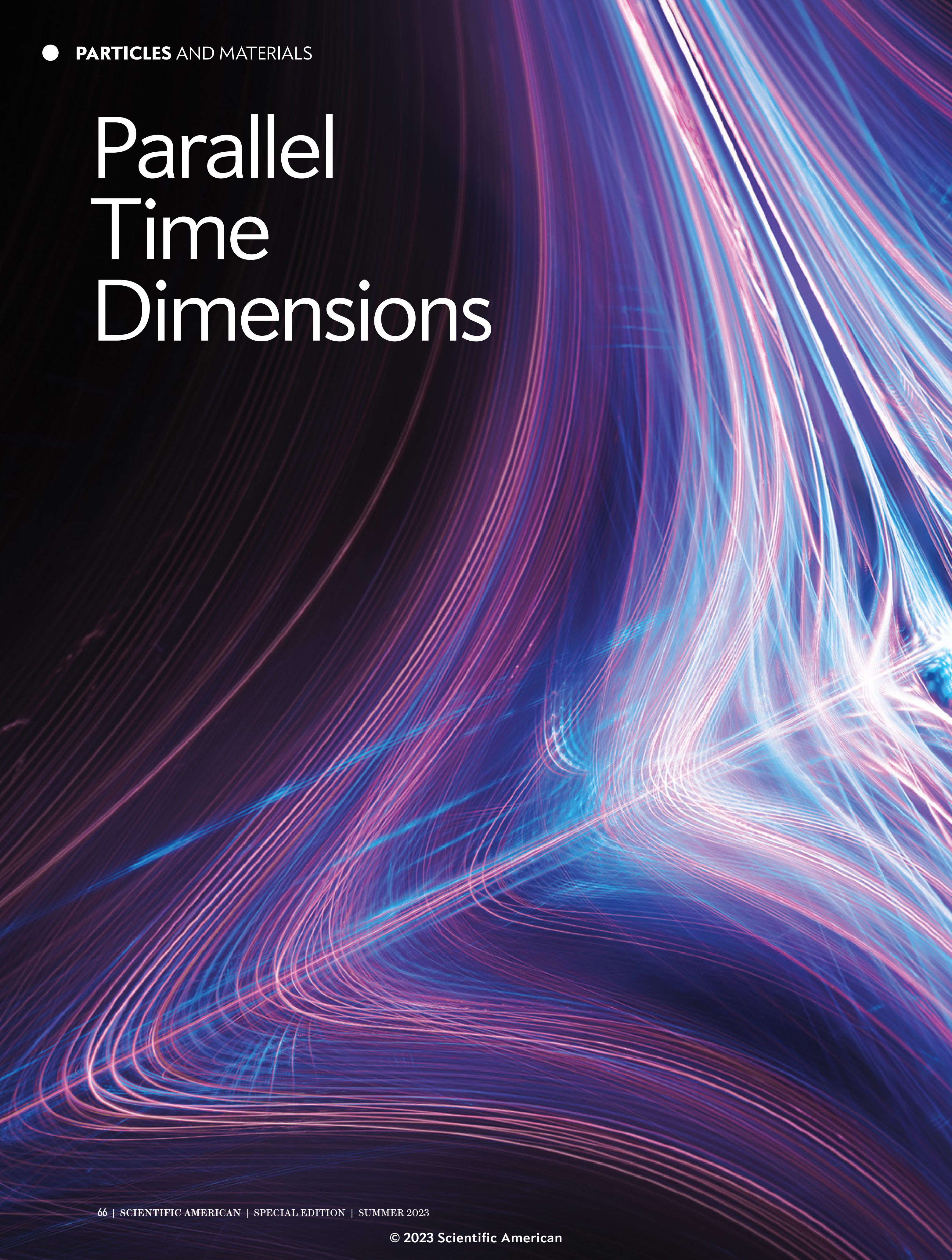
Finally, the equations of general relativity, which embody our best present understanding of spacetime structure, are based on the concept that we can specify a definite distance between any two nearby points. This simple idea, though, is known to break down in at least two extreme conditions: when we extrapolate big bang cosmology to its initial moments and in the central interior of black holes. Elsewhere in physics, breakdown of the equations that describe behavior in a given state of matter is often a signal that the system will undergo a phase transition. Could it be that spacetime itself, under extreme conditions of high pressure, high temperature or rapid change, abandons τ?

Ultimately the concept of time crystals offers a chance for progress both theoretically—in terms of understanding cosmology and black holes from another perspective—and practically. The novel forms of time crystals most likely to be revealed in the coming years should move us closer to more perfect clocks, and they may turn out to have other useful properties. In any case, they are simply interesting, and offer us opportunities to expand our ideas about how matter can be organized.

Frank Wilczek is a theoretical physicist at the Massachusetts Institute of Technology. He won the 2004 Nobel Prize in Physics for his work on the theory of the strong force, and in 2012 he proposed the concept of time crystals.

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Parallel Time Dimensions



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Physicists have devised a mind-bending error-correction technique that could dramatically boost the performance of quantum computers

By Zeeya Merali

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WHEN THE ANCIENT INCAS WANTED TO ARCHIVE TAX AND CENSUS records, they used a device made up of a number of strings called a quipu, which encoded the data in knots. Fast-forward several hundred years, and physicists are on their way to developing a far more sophisticated modern equivalent. Their "quipu" is a new phase of matter created within a quantum computer, their strings are atoms, and the knots are generated by patterns of laser pulses that effectively open up a second dimension of time.

This isn't quite as incomprehensible as it first seems. The new phase is one of many within a family of so-called topological phases, which were first identified in the 1980s. These materials display order not on the basis of how their constituents are arranged—as with the regular spacing of atoms in a crystal—but in their dynamic motions and interactions. Creating a new topological phase—that is, a new "phase of matter"—is as simple as applying novel combinations of electromagnetic fields and laser pulses to bring order or "symmetry" to the motions and states of a substance's atoms. Such symmetries can exist in time rather than space, for example, in induced repetitive motions. Time symmetries can be difficult to see directly, but scientists can investigate them mathematically by imagining a real-world material as a lower-dimensional projection from a hypothetical higher-dimensional space, similar to how a two-dimensional hologram is a lower-dimensional projection of a three-dimensional object. In the case of this newly created phase, which manifests in a strand of ions (electrically charged atoms), physicists can discern its symmetries by considering it as a material that exists in higher-dimensional reality with two time dimensions.

"It is very exciting to see this unusual phase of matter realized in an actual experiment, especially because the mathematical description is based on a theoretical 'extra' time dimension," says team member Philipp Dumitrescu, who was at the Flatiron Institute in New York City when the experiments were carried out. A paper describing the work was published in *Nature* in July 2022.

Opening a portal to an extra time dimension—even just a theoretical one—sounds thrilling, but it was not the researchers' original plan. "We were very much motivated to see what new types of phases could be created," says study co-author Andrew Potter, a quantum physicist at the University of British Columbia. Only after envisioning their proposed new phase did the team members realize it could help protect data being processed in quantum computers from errors.

Standard classical computers encode information as strings of bits—0's or 1's—whereas the predicted power of quantum computers derives from the ability of quantum bits, or qubits, to store values of either 0 or 1, or both, simultaneously (think of Schrödinger's cat, which can be both dead and alive). Most quantum computers encode information in the state of each qubit, for instance, in an internal quantum property of a particle called spin, which can point up or down, corresponding to a 0 or a 1 or in both directions at the same time. But any noise—a stray magnetic field, say—could wreak havoc on a carefully prepared system by flipping spins willy-nilly and even destroying quantum effects entirely, thereby halting calculations.

Potter likens this vulnerability to conveying a message using pieces of string, with each string arranged in the shape of an individual letter and laid out on the floor. "You could read it fine until a small breeze comes along and blows a letter away," he says. To create the more error-proof quantum material, Potter's team looked to topological phases. In a quantum computer that exploits topology, information is not encoded locally in the state of each qubit but is woven across the material globally. "It's like a knot that's hard to undo—like quipu," the Incas' mechanism for storing census and other data, Potter says.

"Topological phases are intriguing because they offer a way to protect against errors that's built into the material," adds study co-author Justin Bohnet, a quantum physicist at computing company Quantinuum in Broomfield, Colo., where the experiments were carried out. "This is different to traditional error-correcting protocols, where you are constantly doing measurements on a small piece of the system to check if errors are there and then going in and correcting them."

Quantinuum's H1 quantum processor is made up of a strand of 10 qubits—10 ytterbium ions—in a vacu-

sakkmesterke/Getty Images (*preceding pages*)

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um chamber, with lasers tightly controlling their positions and states. Such an "ion trap" is a standard technique used by physicists to manipulate ions. In their first attempt to create a topological phase that would be stable against errors, Potter, Dumitrescu and their colleagues sought to imbue the processor with a simple time symmetry by imparting periodic kicks to the ions—all lined up in one dimension—with regularly repeating laser pulses. "Our back-of-the-envelope calculations suggested this would protect [the quantum processor] from errors," Potter says. This is similar to how a steady drumbeat can keep multiple dancers in rhythm.

To see if they were right, the researchers ran the program multiple times on Quantinuum's processor and checked each time to see whether the resulting quantum state of all the qubits matched their theoretical predictions. "It didn't work at all," Potter says with a laugh. "Totally incomprehensible stuff was coming out." Each time, accumulating errors in the system degraded its performance within 1.5 seconds. The team soon realized that it was not enough to just add one time symmetry. In fact, rather than preventing the qubits from being affected by outside knocks and noise, the periodic laser pulses were amplifying tiny hiccups in the system, making small disruptions even worse, Potter explains.

So he and his colleagues went back to the drawing board until, at last, they struck on an insight: if they could concoct a pattern of pulses that was somehow itself ordered (rather than random) yet did not repeat in a regular manner, they might create a more resilient topological phase. They calculated that such a "quasiperiodic" pattern could potentially induce multiple symmetries in the processor's ytterbium qubits while avoiding the unwanted amplifications. The pattern they chose was the mathematically well-studied Fibonacci sequence, in which the next number in the sequence is the sum of the previous two. (So where a regular periodic laser-pulse sequence might alternate between two frequencies from two lasers as A, B, A, B …, a pulsing Fibonacci sequence would run as A, AB, ABA, ABAAB, ABAABABA….)

Although these patterns actually emerged from a rather complex arrangement of two collections of varying laser pulses, the system, according to Potter, can be simply considered as "two lasers pulsing with two different frequencies" that ensure the pulses never temporally overlap. For the purpose of its calculations, the theoretical side of the team imagined these two independent collections of beats along two separate time lines; each collection is effectively pulsing in its own time dimension. These two time dimensions can be traced on the surface of a torus. The quasiperiodic nature of the dual time lines becomes clear by the way they each wrap around the torus again and again "at a weird angle that never repeats on itself," Potter says.

When the team implemented the new program with the quasiperiodic sequence, Quantinuum's processor was indeed protected for the full length of the test: 5.5 seconds. "It doesn't sound like a lot in seconds, but it's a really stark difference," Bohnet says. "It's a clear sign the demonstration is working."

"It's pretty cool," agrees Chetan Nayak, an expert on quantum computing at Microsoft Station Q at the University of California, Santa Barbara, who was not involved in the study. He notes that, in general, two-dimensional spatial systems offer better protection against errors than one-dimensional systems do, but they are harder and more expensive to build. The effective second time dimension created by the team sneaks around this limitation. "Their one-dimensional system acts like a higher-dimensional system in some ways but without the overhead of making a two-dimensional system," he says. "It's the best of both worlds, so you have your cake, and you eat it, too."

> "Their one-dimensional system acts like a higher-dimensional system in some ways but without the overhead of making a two-dimensional system."
> —Chetan Nayak
> *University of California, Santa Barbara*

Samuli Autti, a quantum physicist at Lancaster University in England, who was also not involved with the team, describes the tests as "elegant" and "fascinating" and is particularly impressed that they involve "dynamics"—that is, the laser pulses and manipulations that stabilize the system and move its constituent qubits. Most previous efforts to topologically boost quantum computers relied on less active control methods, making them more static and less flexible. Thus, Autti says, "dynamics with topological protection is a major technological goal."

The name the researchers assigned to their new topological phase of matter recognizes its potentially transformative capabilities, although it is a bit of a mouthful: emergent dynamical symmetry-protected topological phase, or EDSPT. "It'd be nice to think of a catchier name," Potter admits.

There was another unexpected bonus of the project: the original failed test with the periodic pulse sequence revealed that the quantum computer was more error-prone than assumed. "This was a good way of stretching and testing how good Quantinuum's processor is," Nayak says. SA

Zeeya Merali is a freelance writer based in London and author of *A Big Bang in a Little Room* (Basic Books, 2017).

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Mimicking Matter with Light

Experiments that imitate materials with light waves reveal the quantum basis of exotic physical effects

By Charles D. Brown II

Photographs by Spencer Lowell

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INSIDE A HEXAGON-SHAPED ultrahigh vacuum chamber, physicists use laser optics to create optical lattices that mimic the crystal lattices in solid materials.

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MANY SEEMINGLY MUNDANE MATERIALS, such as the stainless steel on refrigerators or the quartz in a countertop, harbor fascinating physics inside them. These materials are crystals, which in physics means they are made of highly ordered repeating patterns of regularly spaced atoms called atomic lattices. How electrons move through a lattice, hopping from atom to atom, determines many of a solid's properties, such as its color, transparency, and ability to conduct heat and electricity. For example, metals are shiny because they contain lots of free electrons that can absorb light and then reemit most of it, making their surfaces gleam.

In certain crystals the behavior of electrons can create properties that are much more exotic. The way electrons move inside graphene—a crystal made of carbon atoms arranged in a hexagonal lattice—produces an extreme version of a quantum effect called tunneling, whereby particles can plow through energy barriers that classical physics says should block them. Graphene also exhibits a phenomenon called the quantum Hall effect: the amount of electricity it conducts increases in specific steps whose size depends on two fundamental constants of the universe. These kinds of properties make graphene intrinsically interesting as well as potentially useful in applications ranging from better electronics and energy storage to improved biomedical devices.

I and other physicists would like to understand what's going on inside graphene on an atomic level, but it's difficult to observe action at this scale with current technology. Electrons move too fast for us to capture the details we want to see. We've found a clever way to get around this limitation, however, by making matter out of light. In place of the atomic lattice, we use light waves to create what we call an optical lattice. Our optical lattice has the exact same geometry as the atomic lattice. In a recent experiment, for instance, my team and I made an optical version of gra-

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phene with the same honeycomb lattice structure as the standard carbon one. In our system, we make cold atoms hop around a lattice of bright and dim light just as electrons hop around the carbon atoms in graphene.

With cold atoms in an optical lattice, we can magnify the system and slow down the hopping process enough to actually see the particles jumping around and make measurements of the process. Our system is not a perfect emulation of graphene, but for understanding the phenomena we're interested in, it's just as good. We can even study lattice physics in ways that are impossible in solid-state crystals. Our experiments revealed special properties of our synthetic material that are directly related to the bizarre physics manifesting in graphene.

TOPOLOGICAL MATERIALS

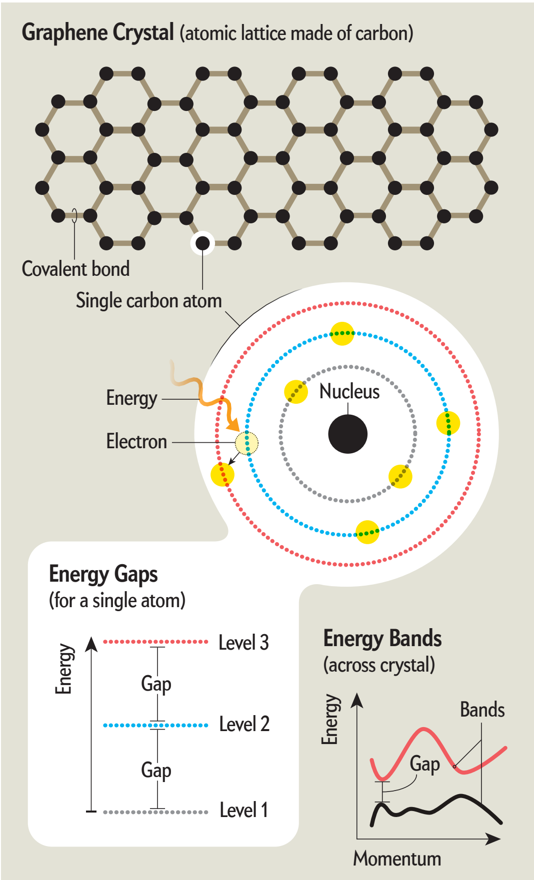
THE CRYSTAL PHENOMENA we investigate result from the way quantum mechanics limits the motion of wavelike particles. After all, although electrons in a crystal have mass, they are both particles and waves (the same is true for our ultracold atoms). In a solid crystal these limits restrict a single electron on a single atom to only one value of energy for each possible movement pattern (called a quantum state). All other amounts of

CHARLES D. BROWN II (*above*) uses optical lattices to probe exotic physics. Notes on a wall (*left*) offer reminders for alignment of optical lattice laser beams and other methods.

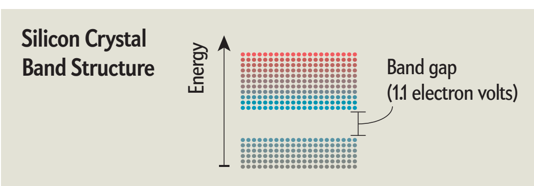
Photograph by Wayne Lawrence (right)

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energy are forbidden. Different states have separate and distinct—discrete—energy values. But a chunk of solid crystal the size of a grape typically contains more atoms (around 10^{23}) than there are grains of sand on Earth. The interactions between these atoms and electrons cause the allowed discrete energy values to spread out and smear into allowed *ranges* of energy called bands. Visualizing a material's energy band structure can immediately reveal something about that material's properties.



For instance, a plot of the band structure of silicon crystal, a common material used to make rooftop solar cells, shows a forbidden energy range—also known as a band gap—that is 1.1 electron volts wide. If electrons can jump from states with energies below this gap to states with energies above the gap, they can flow through the crystal. Fortunately for humanity, the band gap of this abundant material overlaps well with the wavelengths present in sunlight. As silicon crystal absorbs sunlight, electrons begin to flow through it—allowing solar panels to convert light into usable electricity.

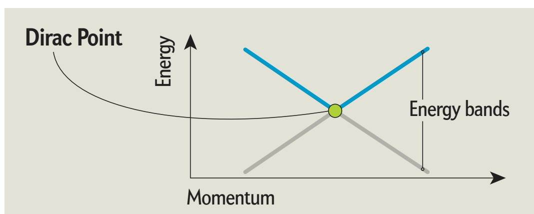


The band structure of certain crystals defines a class of materials known as topological. In mathematics, topology describes how shapes can be transformed without being fundamentally altered. "Transformation" in this context means to deform a shape—to bend or stretch it—without creating or destroying any kind of hole. Topology thus distinguishes baseballs, sesame bagels and shirt buttons based purely on the number of holes in each object.

Topological materials have topological properties hidden in their band structure that similarly allow some kind of transformation while preserving something essential. These topological properties can lead to measurable effects. For instance, some topological materials allow electrons to flow only around their edges and not through their interior. No matter how you deform the material, the current will still flow only along its surface.

I have become particularly interested in certain kinds of topological material: those that are two-dimensional. It may sound odd that 2-D materials exist in our 3-D world. Even a single sheet of standard printer paper, roughly 0.004 inch thick, isn't truly 2-D—its thinnest dimension is still nearly one million atoms thick. Now imagine shaving off most of those atoms until only a single layer of them remains; this layer is a 2-D material. In a 2-D crystal, the atoms and electrons are confined to this plane because moving off it would mean exiting the material entirely.

Graphene is an example of a 2-D topological material. To me, the most intriguing thing about graphene is that its band structure contains special spots known as Dirac points. These are positions where two energy bands take on the same value, meaning that at these points electrons can easily jump from one energy band to another. One way to understand Dirac points is to study a plot of the energy of different bands versus an electron's momentum—a property associated with the particle's kinetic energy. Such plots show how an electron's energy changes with its movement, giving us a direct probe into the physics we're interested in. In these plots, a Dirac point looks like a place where two energy bands touch; at this point they're equal, but away from this point the gap between the bands grows linearly. Graphene's Dirac points and the associated topology are connected to this material's ability to display a form of the quantum Hall effect that's unique even among 2-D materials—the half-integer quantum Hall effect—and the special kind of tunneling possible within it.



ARTIFICIAL CRYSTALS

TO UNDERSTAND what's happening to electrons at Dirac points, we need to observe them up close. Our optical lattice experiments are the perfect way to do this. They offer a highly controllable replica of the

Graphics by Jen Christiansen

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GRADUATE STUDENTS at the University of California, Berkeley, review optical lattice experiment data.

material that we can uniquely manipulate in a laboratory. As substitutes for the electrons, we use ultracold rubidium atoms chilled to temperatures roughly 10 million times colder than outer space. And to simulate the graphene lattice, we turn to light.

Light is both a particle and a wave, which means light waves can interfere with one another, either amplifying or canceling other waves depending on how they are aligned. We use the interference of laser light to make patterns of bright and dark spots, which become the lattice. Just as electrons in real graphene are attracted to certain positively charged areas of a carbon hexagon, we can arrange our optical lattices so ultracold atoms are attracted to or repelled from analogous spots in them, depending on the wavelength of the laser light that we use. Light with just the right energy (resonant light) landing on an atom can change the state and energy of an electron within it, imparting forces on the atom. We typically use "red-detuned" optical lattices, which means the laser light in the lattice has a wavelength that's longer than the wavelength of the resonant light. The result is that the rubidium atoms feel an attraction to the bright spots arranged in a hexagonal pattern.

We now have the basic ingredients for an artificial crystal. Scientists first imagined these ultracold atoms in optical lattices in the late 1990s and constructed them in the early 2000s. The spacing between the lattice points of these artificial crystals is hundreds of nanometers rather than the fractions of a nanometer that separate atoms in a solid crystal. This larger distance means that artificial crystals are effectively magnified versions of real ones, and the hopping process of atoms within them is much slower, allowing us to directly image the movements of the ultracold atoms. In addition, we can manipulate these atoms in ways that aren't possible with electrons.

I was a postdoctoral researcher in the Ultracold Atomic Physics group at the University of California, Berkeley, from 2019 to 2022. The lab there has two special tables (roughly one meter wide by two and a half meters long by 0.3 meter high), each weighing roughly one metric ton and floating on pneumatic legs that dampen vibrations. Atop each table lie hundreds of optical components: mirrors, lenses, light detectors, and more. One table is responsible for producing laser light for trapping, cooling and imaging rubidium atoms. The other table holds an "ultrahigh" vacuum chamber made of steel with a vacuum pressure less than that of low-Earth orbit, along with hundreds more optical components.

The vacuum chamber has multiple, sequential compartments with different jobs. In the first compartment, we heat a five-gram chunk of rubidium metal to more than 100 degrees Celsius, which causes it to emit a vapor of rubidium atoms. The vapor gets blasted into the next compartment like water spraying from a hose. In the second compartment, we use magnetic fields and laser light to slow the vapor down. The sluggish vapor then flows into

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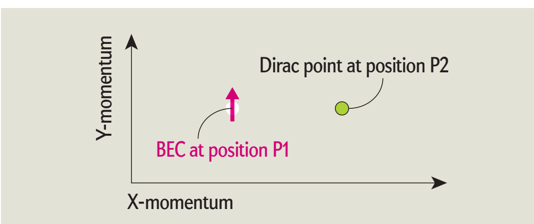
another compartment: a magneto-optical trap, where it is captured by an arrangement of magnetic fields and laser light. Infrared cameras monitor the trapped atoms, which appear on our viewing screen as a bright glowing ball. At this point the atoms are colder than liquid helium.

We then move the cold cloud of rubidium atoms into the final chamber, made entirely of quartz. There we shine both laser light and microwaves on the cloud, which makes the warmest atoms evaporate away. This step causes the rubidium to transition from a normal gas to an exotic phase of matter called a Bose-Einstein condensate (BEC). In a BEC, quantum mechanics allows atoms to delocalize—to spread out and overlap with one another so that all the atoms in the condensate act in unison. The temperature of the atoms in the BEC is less than 100 nanokelvins, one billion times colder than liquid nitrogen.

At this point we shine three laser beams separated by 120 degrees into the quartz cell (their shape roughly forms the letter Y). At the intersection of the three beams, the lasers interfere with one another and produce a 2-D optical lattice that looks like a honeycomb pattern of bright and dark spots. We then move the optical lattice so it overlaps with the BEC. The lattice has plenty of space for atoms to hop around, even though it extends over a region only as wide as a human hair. Finally, we collect and analyze pictures of the atoms after the BEC has spent some time in the optical lattice. As complex as it is, we go through this entire process once every 40 seconds or so. Even after years of working on this experiment, when I see it play out, I think to myself, "Wow, this is incredible!"

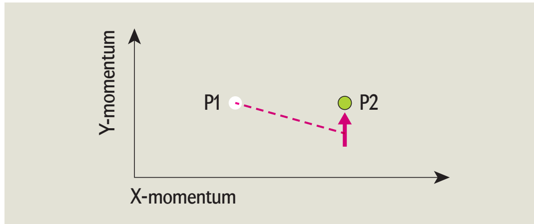
THE SINGULARITY

LIKE REAL GRAPHENE, our artificial crystal has Dirac points in its band structure. To understand why these points are significant topologically, let's go back to our graph of energy versus momentum, but this time let's view it from above so we see momentum plotted in two directions—right and left, and up and down. Imagine that the quantum state of the BEC in the optical lattice is represented by an upward arrow at position one (P1) and that a short, straight path separates P1 from a Dirac point at position two (P2).

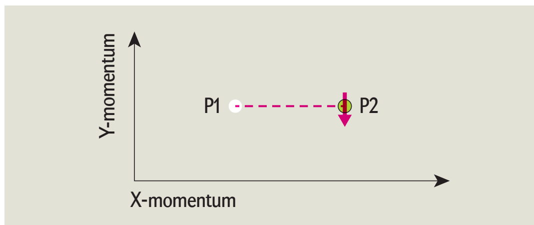


To move our BEC on this graph toward the Dirac point, we need to change its momentum—in other words, we must actually move it in physical space. To put the BEC at the Dirac point, we need to give it the precise momentum values corresponding to that point on the plot. It turns out that it's easier, experimentally, to shift the optical lattice—to change *its* momentum—and leave the BEC as is; this movement gives us the same end result. From an atom's point of view, a stationary BEC in a moving lattice is the same as a moving BEC in a stationary lattice. So we adjust the position of the lattice, effectively giving our BEC a new momentum and moving it over on our plot.

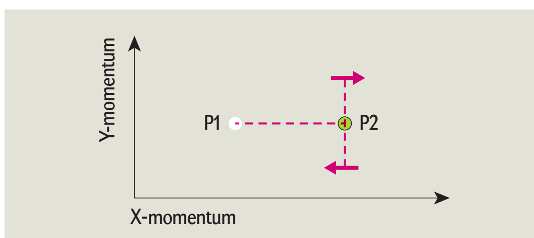
If we adjust the BEC's momentum so that the arrow representing it moves slowly on a straight path from P1 toward P2 but just misses P2 (meaning the BEC has slightly different momentum than it needs to reach P2), nothing happens—its quantum state is unchanged. If we start over and move the arrow even more slowly from P1 toward P2 on a path whose end is even closer to—but still does not touch—P2, the state again is unchanged.



Now imagine that we move the arrow from P1 directly through P2—that is, we change the BEC's momentum so that it's exactly equal to the value at the Dirac point: we will see the arrow flip completely upside down. This change means the BEC's quantum state has jumped from its ground state to its first excited state.



What if instead we move the arrow from P1 to P2, but when it reaches P2, we force it to make a sharp left or right turn—meaning that when the BEC reaches the Dirac point, we stop giving it momentum in its initial direction and start giving it momentum in a direction perpendicular to the first one? In this case, something special happens. Instead of jumping to an excited state as if it had passed straight through the Dirac point and instead of going back down to the ground state as it would if we had turned it fully around, the BEC ends up in a superposition when it exits the Dirac point at a right angle. This is a purely quantum phenomenon in which the BEC enters a state that is both excited and not. To show the superposition, our arrow in the plot rotates 90 degrees.



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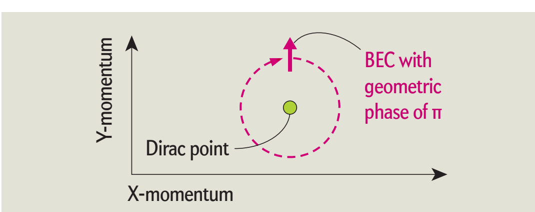
Our experiment was the first to move a BEC through a Dirac point and then turn it at different angles. These fascinating outcomes show that these points, which had already seemed special based on graphene's band structure, are truly exceptional. And the fact that the outcome for the BEC depends not just on whether it passes through a Dirac point but on the direction of that movement shows that at the point itself, the BEC's quantum state can't be defined. This shows that the Dirac point is a singularity—a place where physics is uncertain.

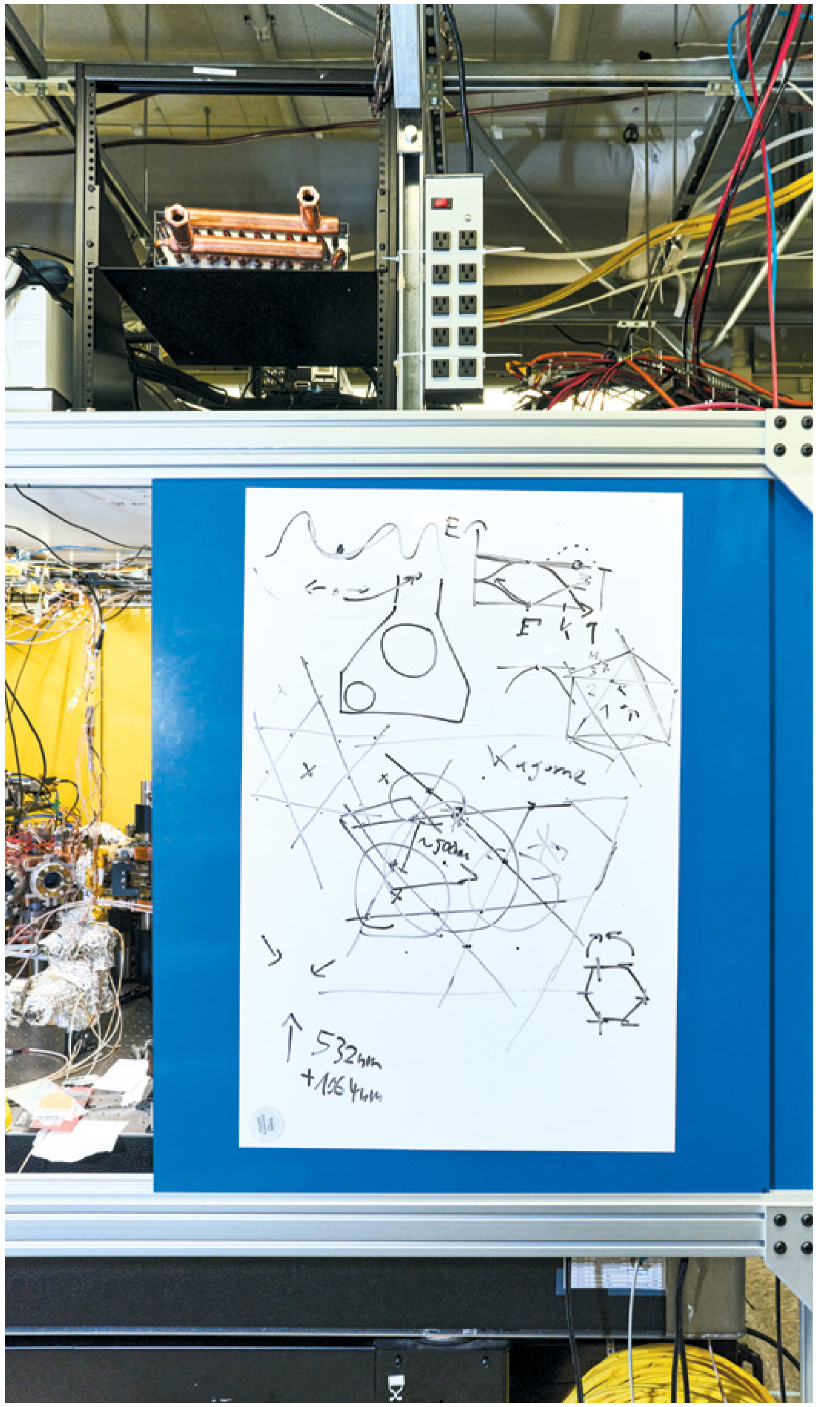
We also measured another interesting pattern. If we moved the BEC faster as it traveled near, but not through, the Dirac point, the point would cause a rotation of the BEC's quantum state that made the point seem larger. In other words, it encompassed a broader range of possible momentum values than just the one precise value at the point. The more slowly we moved the BEC, the smaller the Dirac point seemed. This behavior is uniquely quantum mechanical in nature. Quantum physics is a trip!

Although I just described our experiment in a few paragraphs, it took six months of work to get results. We spent lots of time developing new experimental capabilities that had never been used before. We were often unsure whether our experiment would work. We faced broken lasers, an accidental 10-degree-C temperature spike in the lab that misaligned all the optical components (there went three weeks), and disaster when the air in our building caused the lab's temperature to fluctuate, preventing us from creating a BEC. A great deal of persistent effort carried us through and eventually led to our measuring a phenomenon even more exciting than a Dirac point: another kind of singularity.

GEOMETRIC SURPRISES

BEFORE WE EMBARKED on our experiment, a related project with artificial crystals in Germany showed what happens when a BEC moves in a circular path around a Dirac point. This team manipulated the BEC's momentum so that it took on values that would plot a circle in the chart of left momentum versus up-down momentum. While going through these transformations, the BEC never touched the Dirac point. Nevertheless, moving around the point in this pattern caused the BEC to acquire something called a geometric phase—a term in the mathematical description of its quantum phase that determines how it evolves. Although there is no physical interpretation of a geometric phase, it's a very unusual property that appears in quantum mechanics. Not every quantum state has a geometric phase, so the fact that the BEC had one here is special. What's even more special is that the phase was exactly π.

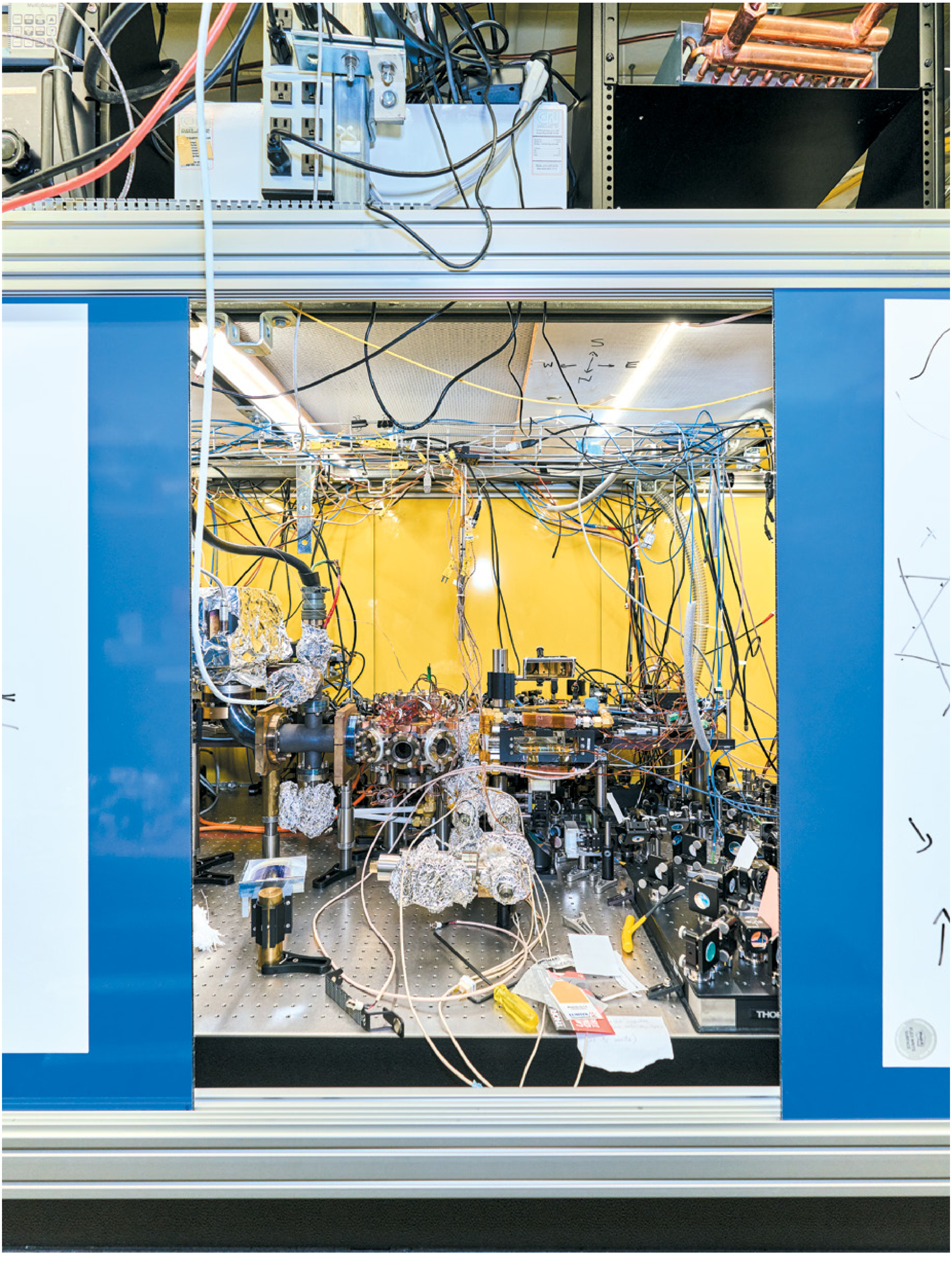




AN ILLUSTRATION helps scientists visualize complex ideas.

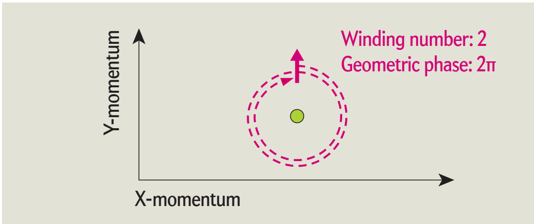
My team decided to try a different technique to confirm the German group's measurement. By measuring the rotation of the BEC's quantum state as we turned it away from the Dirac point at different angles, we reproduced the earlier findings. We discovered that the BEC's quantum state "wraps" around the Dirac point exactly once. Another way to say this is that as you move a BEC through momentum space all the way around a Dirac point, it goes from having all its particles in the ground state to having all its particles in the first excited state, and then they all return to the ground state. This measurement agreed with the German study's results.

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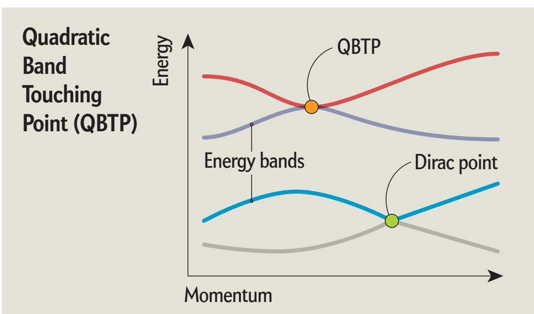


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This wrapping, independent of a particular path or the speed the path is traveled, is a topological property associated with a Dirac point and shows us directly that this point is a singularity with a so-called topological winding number of 1. In other words, the winding number tells us that after a BEC's momentum makes a full circle, it comes back to the state it started in. This winding number also reveals that every time it goes around the Dirac point, its geometric phase increases by π.

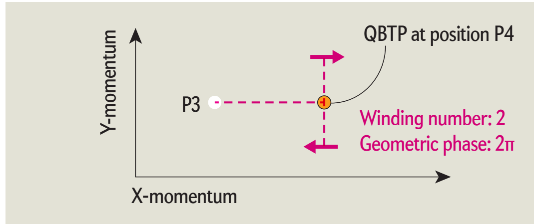


Furthermore, we discovered that our artificial crystal has another kind of singularity called a quadratic band touching point (QBTP). This is another point where two energy bands touch, making it easy for electrons to jump from one to another, but in this case it's a connection between the second excited state and the third (rather than the ground state and the first excited state as in a Dirac point). And whereas the gap between energy bands near a Dirac point grows linearly, in a QBTP it grows quadratically.



In real graphene, the interactions between electrons make QBTPs difficult to study. In our system, however, QBTPs became accessible with just one weird trick.

Well, it's not really so weird, nor is it technically a trick, but we did figure out a specific technique to investigate a QBTP. It turns out that if we give the BEC a kick and get it moving before we load it into the optical lattice, we can access a QBTP and study it with the same method we used to investigate the Dirac point. Here, in the plot of momentum space, we can imagine new points P3 and P4, where P3 is an arbitrary starting point in the second excited band and a QBTP lies at P4. Our measurements showed that if we move the BEC from P3 directly through P4 and turn it at various angles, just as we did with the Dirac point, the BEC's quantum state wraps exactly twice around the QBTP. This result means the BEC's quantum state picked up a geometric phase of exactly 2π. Correspondingly, instead of a topological winding number of 1, like a Dirac point has, we found that a QBTP has a topological winding number of 2, meaning that the state must rotate in momentum space around the point exactly twice before it returns to the quantum state it started in.



This measurement was hard-won. We tried nearly daily for an entire month before it eventually worked—we kept finding fluctuations in our experiment whose sources were hard to pinpoint. After much effort and clever thinking, we finally saw the first measurement in which a BEC's quantum state exhibited wrapping around a QBTP. At that moment I thought, "Oh, my goodness, I *might* actually land a job as a professor." More seriously, I was excited that our measurement technique showed itself to be uniquely suited to reveal this property of a QBTP singularity.

These singularities, with their strange geometric phases and winding numbers, may sound esoteric. But they are directly related to the tangible properties of the materials we study—in this case the special abilities of graphene and its promising future applications. All these changes that occur in the material's quantum state when it moves through or around these points manifest in cool and unusual phenomena in the real world.

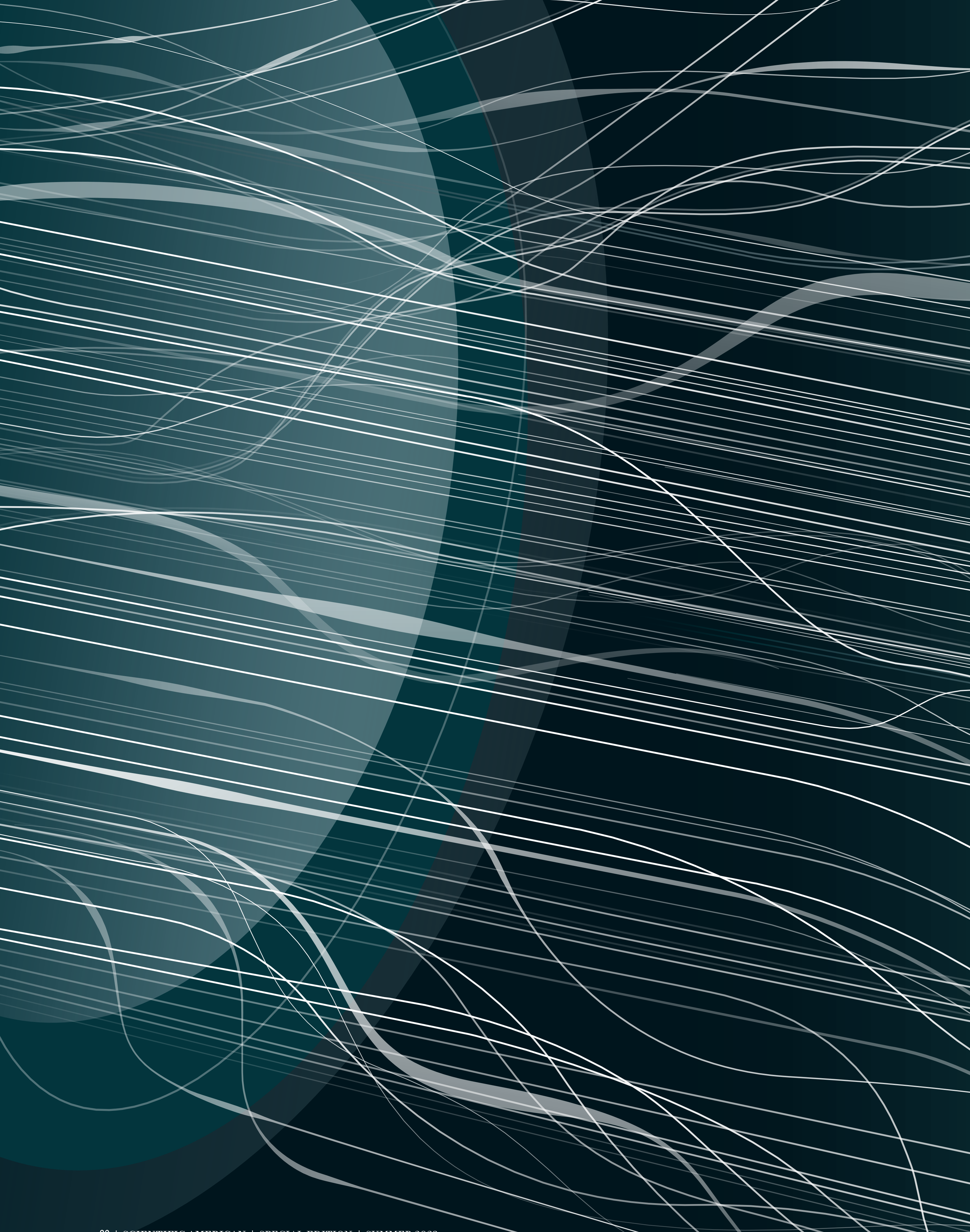
Scientists have predicted, for instance, that QBTPs in solid materials are associated with a type of exotic high-temperature superconductivity, as well as anomalous properties that alter the quantum Hall effect and even electric currents in materials whose flow is typically protected, via topology, from disruption. Before attempting to further investigate this exciting physics, we want to learn more about how interactions between atoms in our artificial crystal change what we observe in our lab measurements.

In real crystals, the electrons interact with one another, and this interaction is usually quite important for the most striking physical effects. Because our experiment was the first of its kind, we took care to ensure that our atoms interacted only minimally to keep things simple. An exciting question we can now pose is: Could interactions cause a QBTP singularity to break apart into multiple Dirac points? Theory suggests this outcome may be possible. We look forward to cranking up the interatomic interaction strength in the lab and seeing what happens. SA

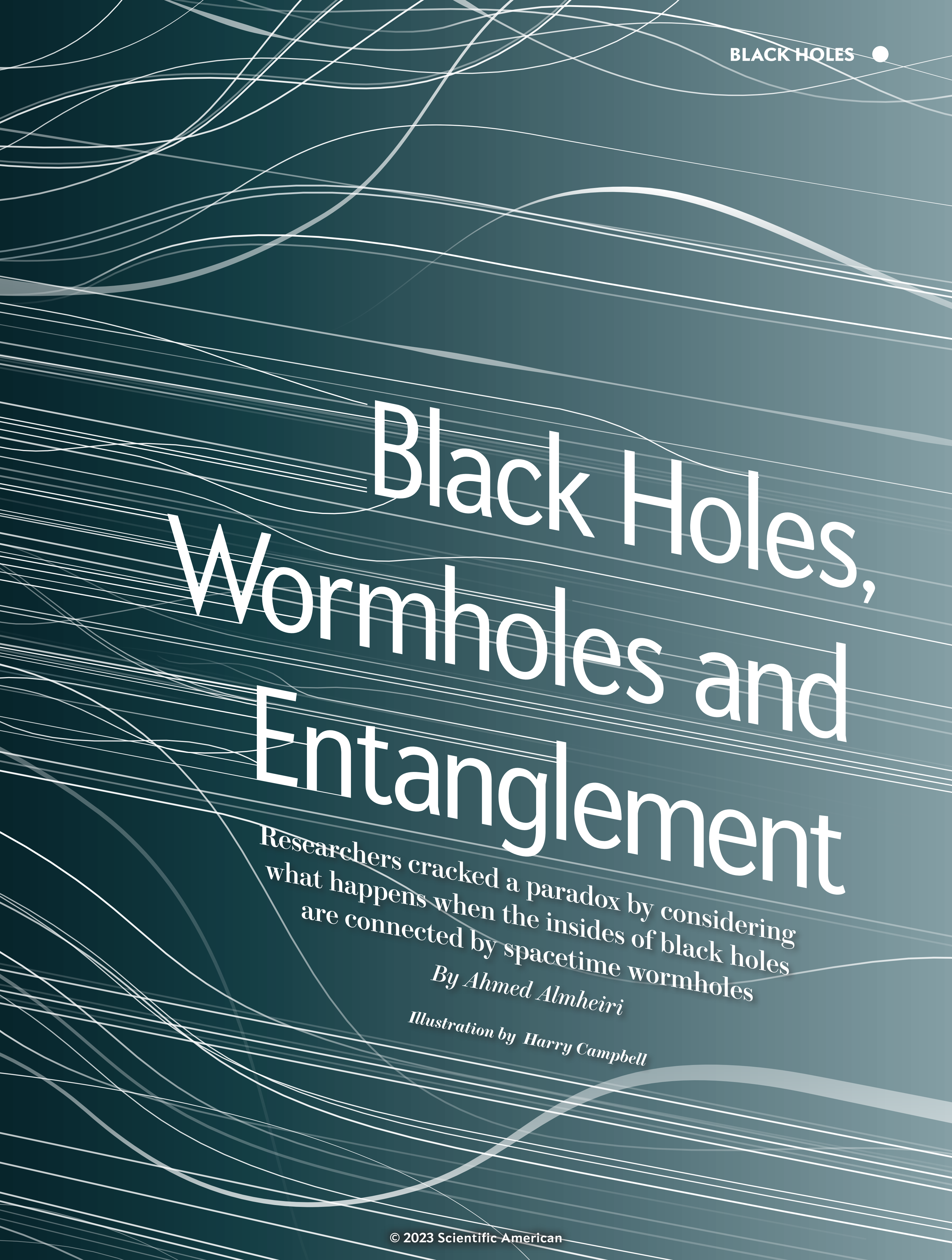
THE ULTRA-HIGH VACUUM CHAMBER is surrounded by a maze of cables, optics and delicate instruments.

Charles D. Brown II is an assistant professor of physics at Yale University, where he uses optical lattices to study the condensed matter physics of quasicrystals.

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Black Holes, Wormholes and Entanglement

Researchers cracked a paradox by considering what happens when the insides of black holes are connected by spacetime wormholes

By Ahmed Almheiri

Illustration by Harry Campbell

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THEORETICAL PHYSICS HAS BEEN IN CRISIS MODE EVER SINCE 1974, WHEN Stephen Hawking argued that black holes destroy information. Hawking showed that a black hole can evaporate, gradually transforming itself and anything it consumes into a featureless cloud of radiation. During the process, information about what fell into the black hole is apparently lost, violating a sacred principle of physics.

This remained an open problem for almost 50 years, but the pieces started falling into place in 2019 through research that I was involved in. The resolution is based on a new understanding of spacetime and how it can be rewired through quantum entanglement, which leads to the idea that part of the inside of a black hole, the so-called island, is secretly on the outside.

To understand how we arrived at these new ideas, we must begin with the inescapable nature of black holes.

A ONE-WAY STREET

NOTHING SEEMS MORE HOPELESS than trying to get out of a black hole—in fact, this impossibility is what defines black holes. They are formed when enough matter is confined within a small enough region that spacetime collapses in on itself in a violent feedback loop of squeezing and stretching that fuels more squeezing and stretching. These tidal forces run to infinity in finite time, marking the abrupt end of an entire region of spacetime at the so-called black hole singularity—the place where time stops and space ceases to make sense.

There is a fine line within the collapsing region that divides the area where escape is possible from the point of no return. This line is called the event horizon. It is the outermost point from which light barely avoids falling into the singularity. Unless a thing travels faster than light—a physical impossibility—it cannot escape from behind the event horizon; it is irretrievably stuck inside the black hole.

The one-way nature of this boundary is not immediately problematic. In fact, it is a robust prediction of the general theory of relativity. The danger starts when this theory interacts with the wild world of quantum mechanics.

SOMETHING OUT OF NOTHING

QUANTUM THEORY redeems black holes from being the greedy monsters they are made out to be. Every calorie of energy they consume they eventually give back in the form of Hawking radiation—energy squeezed out of the vacuum near the event horizon.

The idea of getting something out of nothing may sound absurd, but absurdity is not the worst allegation made against quantum mechanics. The emptiness of the vacuum in quantum theory belies a sea of particles—photons, electrons, gravitons, and more—that conspire to make empty space feel empty. These

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particles come in carefully arranged pairs, acting hand in hand as the glue that holds spacetime together.

Particle pairs that straddle the event horizon of a black hole, however, become forever separated from each other. The newly divorced particles peel away from the horizon in opposite directions, with one member crashing into the singularity and the other escaping the black hole's gravitational pull in the form of Hawking radiation. This process is draining for the black hole, causing it to get lighter and smaller as it emits energy in the form of the outgoing particles. Because of the law that energy must be conserved, the particles trapped inside must then carry negative energy to account for the decrease in the total energy of the black hole.

From the outside, the black hole appears to be burning away (although it happens so slowly, you can't see it happening in real life). When you burn a book, the words on its pages imprint themselves on the pattern of the emanating light and the remaining ashes. This information is thus preserved, at least in principle. If an evaporating black hole were a normal system like the burning book, then the information about what falls into it would be encoded into the emerging Hawking radiation. Unfortunately, this is complicated by the quantum-mechanical relation among the particles across the horizon.

EINSTEIN'S ENEMY

THE ISSUE BEGINS WITH THE END of the pairing of the two particles straddling the event horizon. Despite being separated, they maintain a quantum union that transcends space and time—they are connected by entanglement. Rejected as an absurdity by the physicists who predicted it, quantum entanglement is perhaps one of the weirdest aspects of our universe and arguably one of its most essential. The concept was first concocted by Albert Einstein, Boris Podolsky and Nathan Rosen as a rebuttal against what was then the nascent theory of quantum mechanics. They cited entanglement as a reason the theory must be incomplete—"spooky" is how Einstein famously described the phenomenon.

For a simple example of entanglement, consider two coins in a superposition—the quantum phenomenon of being in multiple states until a measurement is made—of both coins being either heads or tails. The coins aren't facing heads and tails at the same time—that's physically impossible—but the superposition signifies that the chance of observing the pair of coins in either orientation, both heads or both tails, is a probability of one half. There is no chance of ever finding the coins in opposite orientations. The two coins are entangled; the measurement result of one predicts the result of the other with complete certainty. Either coin by itself is completely random, devoid of information, but the randomness of the pair is perfectly correlated.

The scientists were troubled by how the two coins appeared to influence each other without having to come into physical contact. The coins could be in separate galaxies while still maintaining the same amount of entanglement between them. Einstein was unnerved by the apparent "spooky action at a distance" linking the results of the two separate random measurements.

The irony is that Einstein himself is in a superposition of being both wrong and right. He was right to recognize the importance of entanglement in distinguishing quantum mechanics from classical physics. What he got wrong can be summed up with the truism "correlation does not imply causation." Although the fates of the particles are inextricably correlated, the measurement outcome of one does not *cause* the outcome of the other. It turns out that quantum mechanics simply allows for a new, higher degree of correlation than we are used to.

THE IDEA OF GETTING SOMETHING OUT OF NOTHING MAY SOUND ABSURD, BUT ABSURDITY IS NOT THE WORST ALLEGATION MADE AGAINST QUANTUM MECHANICS.

INFORMATION LOST

BECAUSE HAWKING RADIATION is composed of one half of a collection of entangled pairs, it emerges from the black hole in a completely random state—if the particles were coins, they would be observed to be heads or tails with equal probability. Hence, we cannot infer anything useful about the contents of the black hole from the random measurements of the radiation. This means that an evaporating black hole is basically a glorified information shredder, except unlike the mechanical kind, it does a thorough job.

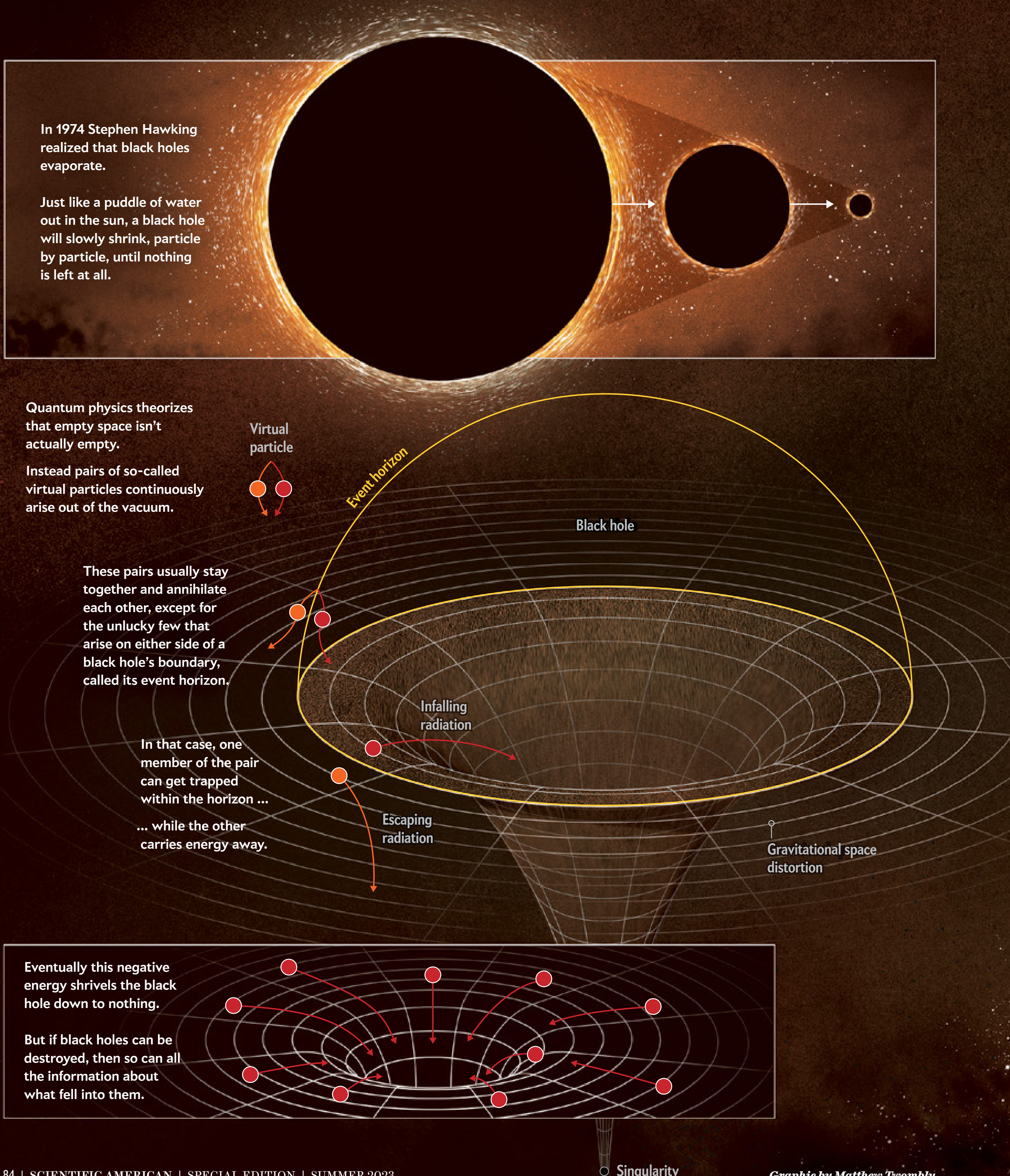
We can measure the lack of information—or the randomness—in the Hawking radiation by thinking about the amount of entanglement between the radiation and the black hole. This is because one member of an entangled pair is always random, and the outside members are all that remains by the end of the evaporation. The calculation of randomness goes by many names, including entanglement entropy, and it grows with every emerging Hawking particle, plateauing at a large value once the black hole has completely disappeared.

This pattern differs from what happens when information is preserved, as in the example of a burning book. In such a case, the entropy may rise initially, but it has to peak and then fall to zero by the end of the process. The intuition behind this rule is clear

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The Black Hole Information Paradox

For almost half a century physicists have agonized over the question of what happens to the stuff that falls into a black hole. If, as theory predicts, black holes destroy information about everything that has ever fallen in, then our theories of nature are in deep, foundational trouble. In recent years, though, scientists have made a breakthrough that might finally solve the puzzle.



Graphic by Matthew Twombly

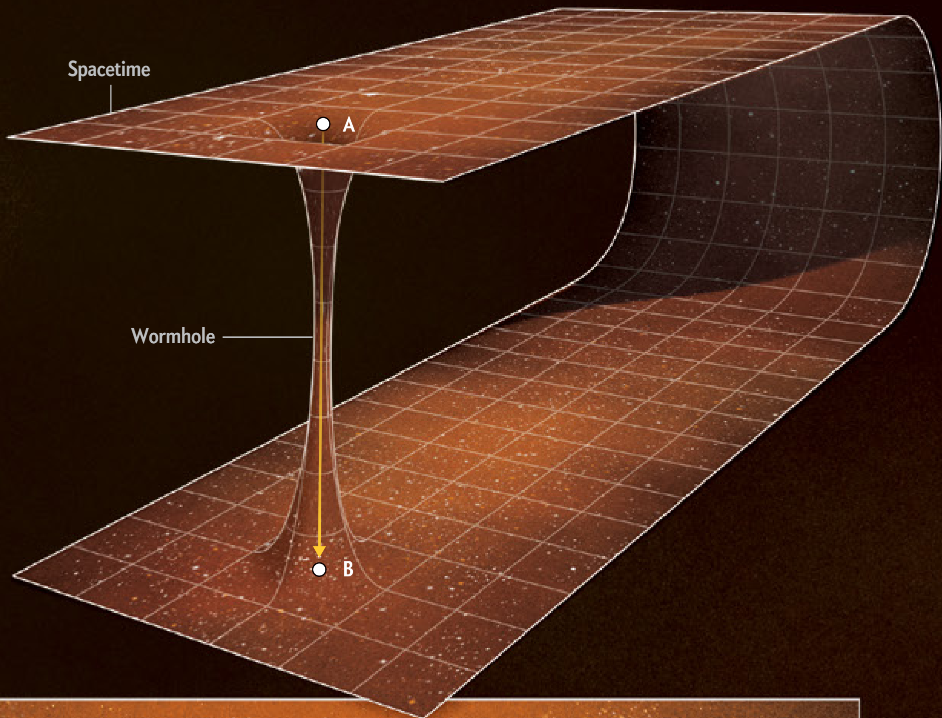
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That seems to break a fundamental law of physics, which says that information can never be destroyed.

This is the paradox.

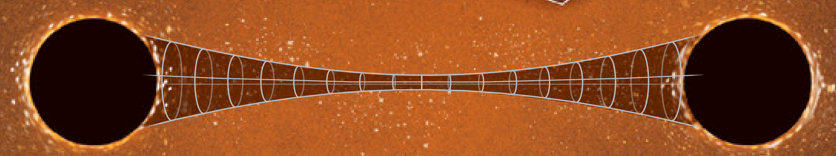
In the past few years a unique solution has revealed itself: wormholes.

Wormholes are theoretical bridges in spacetime that connect two distant spots through a shortcut.



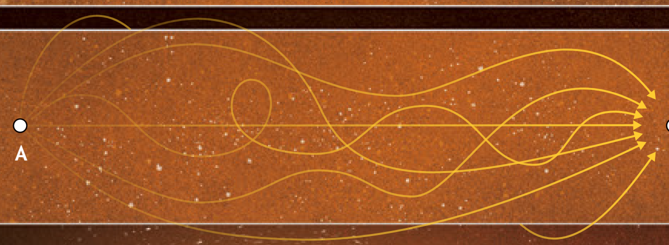
The inside of a black hole could be connected to the inside of another black hole via a wormhole.

Though rare, it's theoretically possible.



And in quantum physics, everything that can happen does happen.

A particle doesn't simply travel along one particular path from point A to point B.



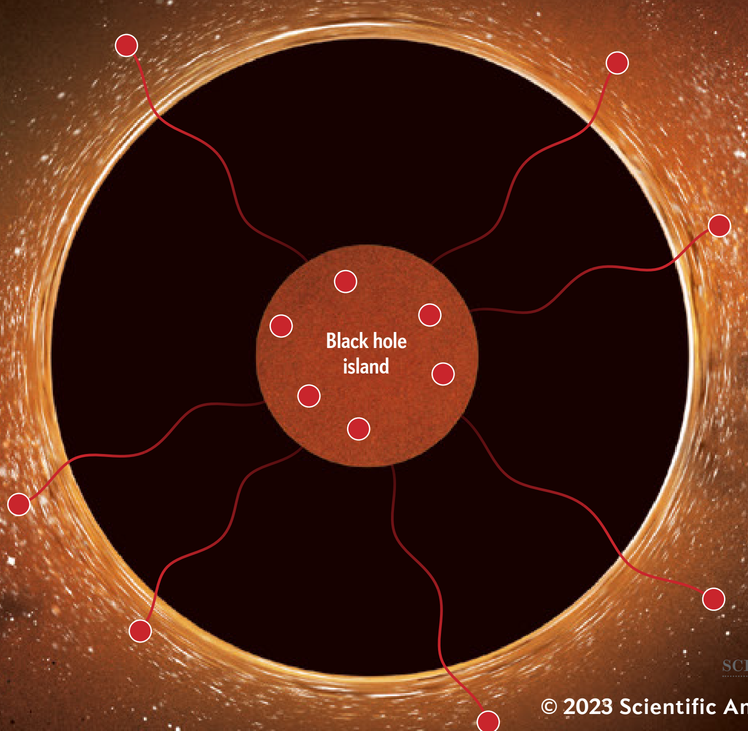
It takes all of them simultaneously.

If wormholes are at the center of black holes, information pulled within may not be destroyed.

Instead the interiors of black holes seem to contain special areas deep inside called islands.

These islands are both inside and outside the black holes, as if they are part of the escaping radiation that is depleting the black holes over time.

And as they escape, the information within them escapes, too.



These new ideas are pretty confounding, even to physicists, who are discovering that the nature of the cosmos and the nature of our reality are even weirder than we could have ever imagined.

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when you think about a standard deck of cards: suppose you are dealt cards from a 52-card deck, one by one, facing down. The entropy of the cards in your possession is simply a measure of your ignorance of what's on the other side of the cards—specifically, the number of possibilities of what they could be. If you have been dealt just one card, the entropy is 52 because there are 52 possibilities. But as you are dealt more, the entropy rises, peaking at 500 trillion for 26 cards, which could be any of 500 trillion different combinations. After this, though, the possible mixes of cards, and thus the entropy, go back down, reaching 52 again when you have 51 cards. Once you have all the cards, you are certain of exactly what you have—the entire deck—and the entropy is zero. This rising and falling pattern of entropy, known as the Page curve, applies to all normal quantum-mechanical systems. The time at which the entropy peaks and then starts to decrease is the Page time.

The destruction of information inside black holes spells disaster for physics because the laws of quantum mechanics stipulate that information cannot be obliterated. This is the famous information paradox—the fact that a sprinkling of quantum mechanics onto the description of black holes leads to a seemingly insurmountable inconsistency. Physicists knew we needed a more complete understanding of quantum-gravitational physics to generate the Page curve for the Hawking radiation. Unsurprisingly, this task proved difficult.

EVENTUALLY MY COLLEAGUES AND I REALIZED THAT BOTH THE INFORMATION PARADOX AND THE NEWER FIREWALL PARADOX AROSE BECAUSE OUR ATTEMPTS TO MELD QUANTUM MECHANICS AND BLACK HOLE PHYSICS WERE TOO TIMID.

AN EVENTFUL HORIZON

PART OF THE CHALLENGE was that no minor tweaking of the evaporation process was sufficient to generate the Page curve and send the entropy back down to zero. What we needed was a drastic reimagining of the structure of a black hole.

In a paper I published in 2013 with Donald Marolf, the late Joseph Polchinski, and Jamie Sully (known collectively as AMPS), we tried out several ways to modify the picture of evaporating black holes using a series of gedankenexperiments—the German term for the kind of thought experiments Einstein popularized. Through our trials we concluded that to save the sanctity of information, one of two things had to give: either physics must be nonlocal—allowing for information to instantaneously disappear from the interior and appear outside the event horizon—or a new process must kick in at the Page time. To preclude the increase of entropy, this process would have to break the entanglement between the particle pairs across the event horizon. The former option—making physics nonlocal—was too radical, so we decided to go with the latter.

This modification helps to preserve information, but it poses another paradox. Recall that the entanglement across the horizon was a result of having empty space there—the way the vacuum is maintained by a sea of entangled pairs of particles. The entanglement is key; breaking it comes at the cost of creating a wall of extremely high-energy particles, which our group named the firewall. Having such a firewall at the horizon would forbid anything from entering the black hole. Instead infalling matter would be vaporized on contact. The black hole at the Page time would suddenly lose its interior, and spacetime would come to an end, not at the singularity deep inside the black hole but right there at the event horizon. This conclusion is known as the firewall paradox, a catch-22 that meant any solution to the information paradox must come at the cost of destroying what we know about black holes. If ever there were a quagmire, this would be it.

FLUCTUATING WORMHOLES

EVENTUALLY MY COLLEAGUES and I realized that both the information paradox and the newer firewall paradox arose because our attempts to meld quantum mechanics and black hole physics were too timid. It wasn't enough to apply quantum mechanics to only the matter present in black holes—we had to devise a quantum treatment of the black hole spacetime as well. Although quantum effects on spacetime are usually very small, they could be enhanced by the large entanglement produced by the evaporation. Such an effect may be subtle, but its implications would be huge.

To consider the quantum nature of spacetime, we relied on a technique designed by Richard Feynman called the path integral of quantum mechanics. The idea is based on the weird truth that, according to quantum theory, particles don't simply travel along a single path from point A to point B—they travel along *all* the different paths connecting the two points. The path integral is a way of describing a particle's travels in terms of a quantum superposition of all possible routes. Similarly, a quantum spacetime can be in a superposition of different complicated shapes evolving in different ways. For instance, if we start and end with two regular black holes, the quantum spacetime within them has a nonzero probabil-

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ity of creating a short-lived wormhole that temporarily bridges their interiors.

Usually the probability of this happening is vanishingly slim. When we carry out the path integral in the presence of the Hawking radiation of multiple black holes, however, the large entanglement between the Hawking radiation and the black hole interiors amplifies the likelihood of such wormholes. This realization came to me through work I did in 2019 with Thomas Hartman, Juan Maldacena, Edgar Shaghoulian and Amirhossein Tajdini, and it was also the result of an independent collaboration by Geoffrey Penington, Stephen Shenker, Douglas Stanford and Zhenbin Yang.

ISLANDS BEYOND THE HORIZON

WHY DOES IT MATTER if some black holes are connected by wormholes? It turns out that they modify the answer of how much entanglement entropy there is between the black hole and its Hawking radiation. The key is to measure this entanglement entropy in the presence of multiple copies of the system. This is known as the replica trick.

The relevant physical effect of these temporary wormholes is to swap out the interiors among the different black holes. This happens literally: what was in one black hole gets shoved into one of the other copies far away, and the original black hole assumes a new spacetime interior from a different one. The swapped region of the black hole interior is called the island, and it encompasses almost the entire interior up to the event horizon.

The swapping is exactly what the doctor ordered! Focusing on one of the black holes and its Hawking radiation, the swapped-out island takes with it all the partner particles that are entangled with the outgoing Hawking radiation, and hence, technically, there is no entanglement between the black hole and its radiation PDF Downloaded@mobilism.org

Including this potential effect of wormholes produces a new formula for the entanglement entropy of the radiation when applied to a single copy of the system. Instead of Hawking's original calculation, which simply counts the number of Hawking particles outside a black hole, the new formula curiously treats the island as if it were outside and a part of the exterior Hawking radiation. Therefore, the entanglement between the island and the exterior should not be counted toward the entropy. Instead the entropy that it predicts comes almost entirely from the probability of the swap actually occurring, which is equal to the area of the boundary of the island—roughly the area of the event horizon—divided by Newton's gravitational constant. As the black hole shrinks, this contribution to the entropy decreases. This is the island formula for the entanglement entropy of the Hawking radiation.

The final step in computing the entropy is to take the minimum between the island formula and Hawking's original calculation. This gives us the Page curve that we've been after. Initially we calculate the entanglement entropy of the radiation with Hawking's original formula because the answer starts off smaller than the area of the event horizon of the black hole. But as the black hole evaporates, the area shrinks, and the new formula takes the baton as the true representative of the radiation's entanglement entropy.

What is remarkable about this result is that it solves two paradoxes with one formula. It appears to address the firewall paradox by supporting the option of nonlocality that my AMPS group originally dismissed. Instead of breaking the entanglement at the horizon, we are instructed to treat the inside—the island—as part of the outside. The island itself becomes nonlocally mapped to the outside. And the formula solves the information paradox by revealing how black holes produce the Page curve and preserve information.

Let's take a step back and think about how we got here. The origins of the information paradox can be traced back to the incompatibility between the sequestering of information by the event horizon and the quantum-mechanical requirement of information flow outside the black hole. Naive resolutions of this tension lead to drastic modifications of the structure of black holes; however, subtle yet dramatic effects from fluctuating wormholes change everything. What emerges is a self-consistent picture that lets a black hole retain its regular structure as predicted by general relativity, albeit with the presence of an implicit though powerful nonlocality. This nonlocality is screaming that we should consider a portion of the black hole's interior—the island—as part of the exterior, as a single unit with the outside radiation. Thus, information can escape a black hole not by surmounting the insurmountable event horizon but by simply falling deeper into the island.

Despite the excitement of this breakthrough, we have only begun to explore the implications of spacetime wormholes and the island formula. Curiously, while they ensure that the island is mapped onto the radiation, they do not generate a definite prediction for specific measurements of the Hawking radiation. What they do teach us, however, is that wormholes are the missing ingredient in Hawking's original estimation of the randomness in the radiation and that gravity is in fact smart enough to comply with quantum mechanics.

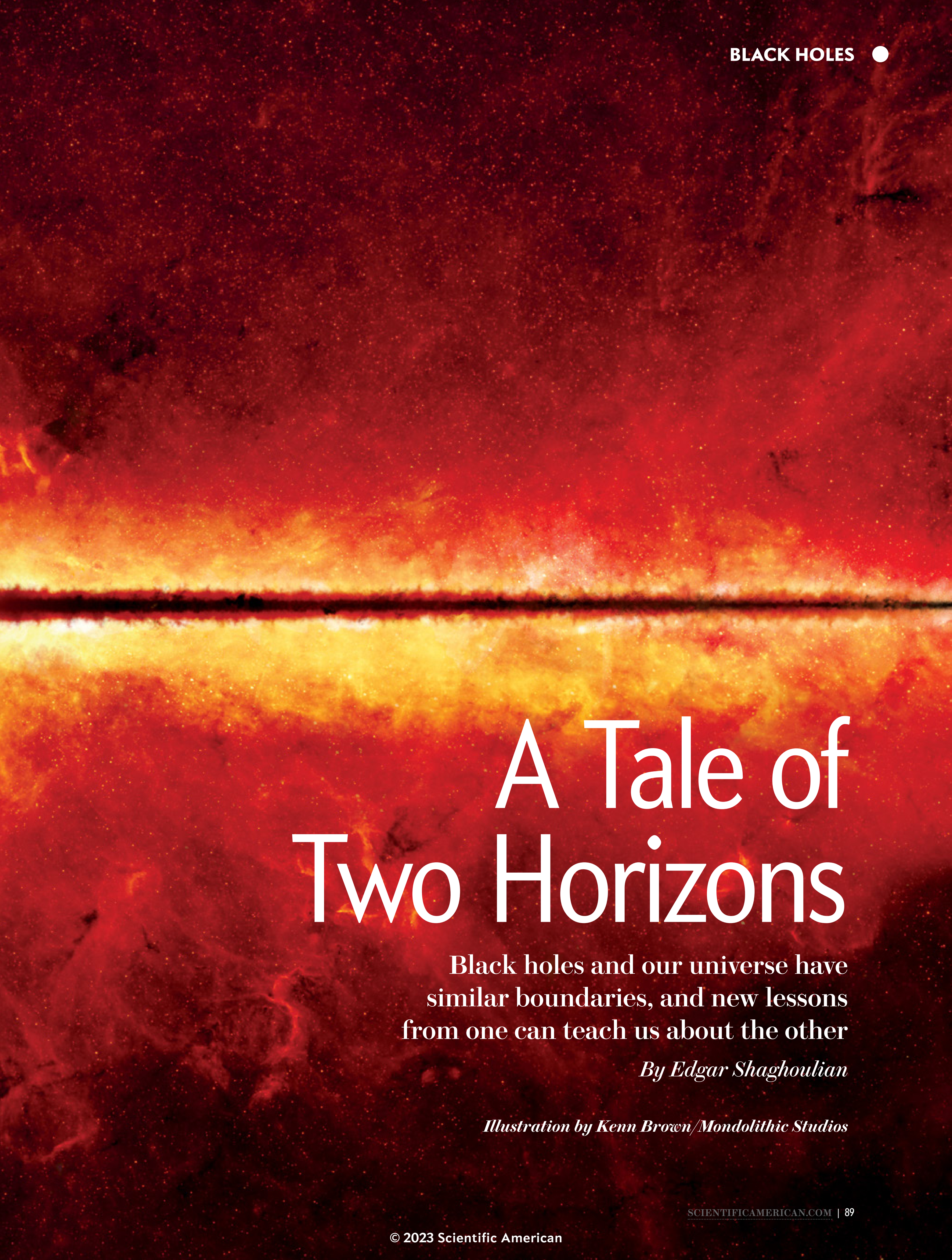
Through these wormholes, gravity harnesses the power of entanglement to achieve nonlocality, which is just as unnerving to us as the entanglement that originally spooked Einstein. We must admit that, at some level, Einstein was right after all. SA

Ahmed Almheiri is a theoretical physicist at New York University in Abu Dhabi, United Arab Emirates, where he studies the connections between quantum information and quantum gravity.

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A Tale of Two Horizons

Black holes and our universe have similar boundaries, and new lessons from one can teach us about the other

By Edgar Shaghoulian

Illustration by Kenn Brown/Mondolithic Studios

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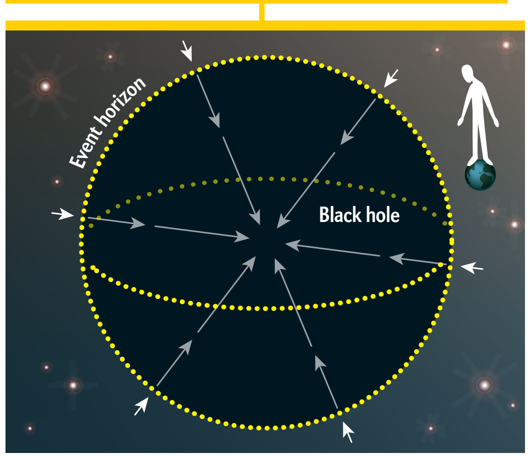
WHERE DID THE UNIVERSE COME FROM? WHERE IS IT HEADED? ANSWERING these questions requires that we understand physics on two vastly different scales: the cosmological, referring to the realm of galaxy superclusters and the cosmos as a whole, and the quantum—the counterintuitive world of atoms and nuclei.

For much of what we would like to know about the universe, classical cosmology is enough. This field is governed by gravity as dictated by Einstein's general theory of relativity, which doesn't concern itself with atoms and nuclei. But there are special moments in the lifetime of our universe—such as its infancy, when the whole cosmos was the size of an atom—for which this disregard for small-scale physics fails us. To understand these eras, we need a quantum theory of gravity that can describe both the electron circling an atom and Earth moving around the sun. The goal of quantum cosmology is to devise and apply a quantum theory of gravity to the entire universe.

Quantum cosmology is not for the faint of heart. It is the Wild West of theoretical physics, with little more than a handful of observational facts and clues to guide us. Its scope and difficulty have called out to young and ambitious physicists like mythological sirens, only to leave them foundering. But there is a palpable feeling that this time is different and that recent breakthroughs from black hole physics—which also required understanding a regime where quantum mechanics and gravity are equally important—could help us extract some answers in quantum cosmology. The fresh optimism was clear at a recent virtual physics conference I attended, which had a dedicated discussion session about the crossover between the two fields. I expected this event to be sparsely attended, but instead many of the luminaries in physics were there, bursting with ideas and ready to get to work.

EVENT HORIZONS

THE FIRST INDICATION that there is any relation between black holes and our universe as a whole is that both manifest "event horizons"—points of no return beyond which two people seemingly fall out of contact forever. A black hole attracts so strongly that at some point even light—the fastest thing in the universe—cannot escape its pull. The boundary where light becomes trapped is thus a spherical event horizon around the center of the black hole.

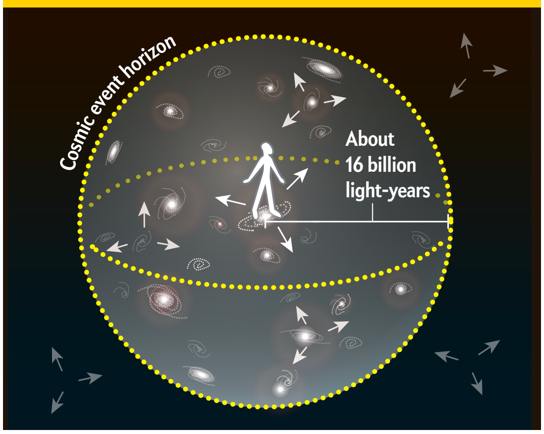


Our universe, too, has an event horizon—a fact confirmed by the stunning and unexpected discovery in 1998 that not only is space expanding, but its expansion is *accelerating*. Whatever is causing this speedup has been called dark energy. The acceleration traps light just as black holes do: as the cosmos expands, regions of space repel one another so strongly that at some point not even light can overcome the separation. This inside-out situation leads to a spherical cosmological event horizon that surrounds us, leaving everything beyond a certain distance in darkness. There is a crucial difference between cosmological and black hole event horizons, however. In a black hole, spacetime is collapsing toward a single point—the singularity. In the universe at large, all of space is uniformly growing, like the surface of a balloon that is being inflated. This means that creatures in faraway galaxies will have their own distinct spherical event horizons, which surround

Graphics by Jen Christiansen

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them instead of us. Our current cosmological event horizon is about 16 billion light-years away. As long as



this acceleration continues, any light emitted today that is beyond that distance will never reach us. (Cosmologists also speak of a particle horizon, which confusingly is often called a cosmological horizon as well. This refers to the distance beyond which light emitted in the early universe has not yet had time to reach us here on Earth. In our tale, we will be concerned only with the cosmological event horizon, which we will often just call the cosmological horizon. These are unique to universes that accelerate, like ours.)

The similarities between black holes and our universe don't end there. In 1974 Stephen Hawking showed that black holes are not completely black: because of quantum mechanics, they have a temperature and therefore emit matter and radiation, just as all thermal bodies do. This emission, called Hawking radiation, is what causes black holes to eventually evaporate away. It turns out that cosmological horizons also have a temperature and emit matter and radiation because of a very similar effect. But because cosmological horizons surround us and the radiation falls inward, they reabsorb their own emissions and therefore do not evaporate away like black holes.

Hawking's revelation posed a serious problem: if black holes can disappear, so can the information contained within them—which is against the rules of quantum mechanics. This is known as the black hole information paradox, and it is a deep puzzle complicating the quest to combine quantum mechanics and gravity. But in 2019 scientists made dramatic progress. Through a confluence of conceptual and technical advances, physicists argued that the information inside a black hole can actually be accessed from the Hawking radiation that leaves the black hole. (For more on how scientists figured this out, see the article on page 80 by my colleague Ahmed Almheiri.)

This discovery has reinvigorated those of us studying quantum cosmology. Because of the mathematical similarities between black holes and cosmological horizons, many of us have long believed that we couldn't understand the latter without understanding the former. Figuring out black holes became a warm-up problem—one of the hardest of all time. We haven't fully solved our warm-up problem yet, but now we have a new set of technical tools that provide beautiful insight into the interplay of gravity and quantum mechanics in the presence of black hole event horizons.

ENTROPY AND THE HOLOGRAPHIC PRINCIPLE

PART OF THE RECENT PROGRESS on the black hole information paradox grew out of an idea called the holographic principle, put forward in the 1990s by Gerard 't Hooft of Utrecht University in the Netherlands and Leonard Susskind of Stanford University. The holographic principle states that a theory of quantum gravity that can describe black holes should be formulated not in the ordinary three spatial dimensions that all other physical theories use but instead in two dimensions of space, like a flat piece of paper. The primary argument for this approach is quite simple: a black hole has an entropy—a measure of how much stuff you can stick inside it—that is proportional to the two-dimensional area of its event horizon.

Contrast this with the entropy of a more traditional system—say, a gas in a box. In this case, the entropy is proportional to the three-dimensional volume of the box, not the area. This is natural: you can stick something at every point in space inside the box, so if the volume grows, the entropy grows. But because of the curvature of space within black holes, you can actually increase the volume without affecting the area of the horizon, and this will not affect the entropy! Even though it naively seems you have three dimensions of space to stick stuff in, the black hole entropy formula tells you that you have only two dimensions of space, an area's worth. So the holographic principle says that because of the presence of black holes, quantum gravity should be formulated as a more prosaic nongravitational quantum system in fewer dimensions. At least then the entropies will match.

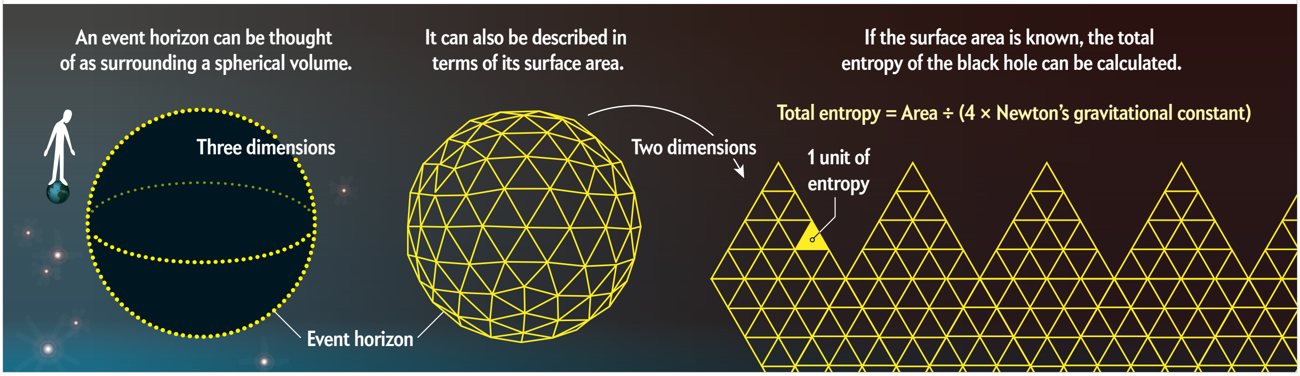
The idea that space might not be truly three-dimensional is rather compelling, philosophically. At least one dimension of it might be an emergent phenomenon that arises from its deeper nature rather than being explicitly hardwired into the fundamental laws. Physicists who study space now understand that it can emerge from a large collection of simple constituents, similar to other emergent phenomena such as consciousness, which seems to arise from basic neurons and other biological systems.

One of the most exciting aspects of the progress in the black hole information paradox is that it points toward a more general understanding of the holographic principle, which previously had been made precise only in situations very different from our real universe. In the calculations from 2019, however, the way the information inside the black hole is encoded in the Hawking radiation is mathematically analogous to how a gravitational system is encoded in a lower-

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The Holographic Principle

An important concept for understanding black holes is the holographic principle. The principle states that a quantum theory of gravity that can describe black holes should be formulated in two dimensions—like the surface of their spherical event horizons—not three, like the volume inside. The reason has to do with the black hole's entropy, which is a measure of the amount of stuff you can stick inside of it. This entropy depends on the area of the black hole, not the volume.



dimensional nongravitational system according to the holographic principle. And these techniques can be used in situations more like our universe, giving a potential avenue for understanding the holographic principle in the real world. A remarkable fact about cosmological horizons is that they also have an entropy, given by the exact same formula as the one we use for black holes. The physical interpretation of this entropy is much less clear, and many of us hope that applying the new techniques to our universe will shed light on this mystery. If the entropy is measuring how much stuff you can stick beyond the horizon, as with black holes, then we will have a sharp bound on how much stuff there can be in our universe.

OUTSIDE OBSERVERS

THE RECENT PROGRESS on the black hole information paradox suggests that if we collect all the radiation from a black hole as it evaporates, we can access the information that fell inside the black hole. One of the most important conceptual questions in cosmology is whether the same is possible with cosmological event horizons. We think they radiate like black holes, so can we access what is beyond our cosmological event horizon by collecting its radiation? Or is there some other way to reach across the horizon? If not, then most of our vast, rich universe will eventually be lost forever. This is a grim image of our future—we will be left in the dark.

Almost all attempts to get a handle on this question have required physicists to artificially extricate themselves from the accelerating universe and imagine viewing it from the outside. This is a crucial simplifying assumption, and it more closely mimics a black hole, where we can cleanly separate the observer from the system simply by placing the observer far away. But there seems to be no escaping our cosmological horizon; it surrounds us, and it moves if we move, making this problem much more difficult. Yet if we want to apply our new tools from the study of black holes to the problems of cosmology, we must find a way to look at the cosmic horizon from the outside.

There are different ways to construct an outsider view. One of the simplest is to consider a hypothetical auxiliary universe that is quantum-mechanically entangled with our own and investigate whether an observer in the auxiliary universe can access the information in our cosmos, which is beyond the observer's horizon. In work I did with Thomas Hartman and Yikun Jiang, both at Cornell University, we constructed examples of auxiliary universes and other scenarios and showed that the observer can access information beyond the cosmological horizon in the same way that we can access information beyond the black hole horizon. (A complementary paper by Yiming Chen of Princeton University, Victor Gorbenko of EPFL in Switzerland and Juan Maldacena of the Institute for Advanced Study [IAS] in Princeton, N.J., showed similar results.)

But these analyses all have one serious deficiency: when we investigated "our" universe, we used a model universe that is *contracting* instead of expanding. Such universes are much simpler to describe in the context of quantum cosmology. We don't completely understand why, but it's related to the fact that we can think of the interior of a black hole as a contracting universe where everything is getting squished together. In this way, our newfound understanding of black holes could easily help us study this type of universe.

Even in these simplified situations, we are puzzling our way through some confusing issues. One problem is that it's easy to construct multiple simultaneous outsider views so that each outsider can access the information in the contracting universe. But this means multiple

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people can reach the same piece of information and manipulate it independently. Quantum mechanics, however, is exacting: not only does it forbid information from being destroyed, it also forbids information from being replicated. This idea is known as the no-cloning theorem, and the multiple outsiders seem to violate it. In a black hole, this isn't a problem, because although there can still be many outsiders, it turns out that no two of them can independently access the same piece of information in the interior. This limit is related to the fact that there is only one black hole and therefore just one event horizon. But in an expanding spacetime, different observers have different horizons. Recent work that Adam Levine of the Massachusetts Institute of Technology and I did together, however, suggests that the same technical tools from the black hole context work to avoid this inconsistency as well.

TOWARD A TRUER THEORY

ALTHOUGH THERE HAS BEEN EXCITING PROGRESS, so far we have not been able to directly apply what we learned about black hole horizons to the cosmological horizon in our universe because of the differences between these two types of horizons.

The ultimate goal? No outsider view, no contracting universe, no work-arounds: we want a complete quantum theory of our expanding universe, described from our vantage point within the belly of the beast. Many physicists believe our best bet is to come up with a holographic description, meaning one using fewer than the usual three dimensions of space. There are two ways we can do this. The first is to use tools from string theory, which treats the elementary particles of nature as vibrating strings. When we configure this theory in exactly the right way, we can provide a holographic description of certain black hole horizons. We hope to do the same for the cosmological horizon. Many physicists have put a lot of work into this approach, but it has not yet yielded a complete model for an expanding universe like ours.

The other way to divine a holographic description is by looking for clues from the properties that such a description should have. This approach is part of the standard practice of science—use data to construct a theory that reproduces the data and hope it makes novel predictions as well. In this case, however, the data themselves are also theoretical. They are things we can reliably calculate even without a complete understanding of the full theory, just as we can calculate the trajectory of a baseball without using quantum mechanics. The idea works as follows: we calculate various things in classical cosmology, maybe with a little bit of quantum mechanics sprinkled in, but we try to avoid situations where quantum mechanics and gravity are equally important. This forms our theoretical data. For example, Hawking radiation is a piece of theoretical data. And what must be true is that the full, exact theory of quantum cosmology should be able to reproduce this theoretical datum in an appropriate regime, just as quantum mechanics can reproduce the trajectory of a baseball (albeit in a much more complicated way than classical mechanics).

Leading the charge in extracting these theoretical data is a powerful physicist with a preternatural focus on the problems of quantum cosmology: Dionysios Anninos of King's College London has been working on the subject for more than a decade and has provided many clues toward a holographic description. Others around the world have also joined the effort, including Edward Witten of IAS, a figure who has towered over quantum gravity and string theory for decades but who tends to avoid the Wild West of quantum cosmology. With his collaborators Venkatesa Chandrasekaran of IAS, Roberto Longo of the University of Rome Tor Vergata and Geoffrey Penington of the University of California, Berkeley, he is investigating how the inextricable link between an observer and the cosmological horizon affects the mathematical description of quantum cosmology.

Sometimes we are ambitious and try to calculate theoretical data when quantum mechanics and gravity are equally important. Inevitably we have to impose some rule or guess about the behavior of the full, exact theory in such instances. Many of us believe that one of the most important pieces of theoretical data is the amount and pattern of entanglement between constituents of the theory of quantum cosmology. Susskind and I formulated distinct proposals for how to compute these data, and in hundreds of e-mails exchanged during the pandemic, we argued incessantly over which was more reasonable. Earlier work by Eva Silverstein of Stanford, another brilliant physicist with a long track record in quantum cosmology, and her collaborators provides yet another proposal for computing these theoretical data.

The nature of entanglement in quantum cosmology is a work in progress, but it seems clear that nailing it will be an important step toward a holographic description. Such a concrete, calculable theory is what the subject desperately needs, so that we can compare its outputs with the wealth of theoretical data that are accumulating from scientists. Without this theory, we will be stuck at a stage akin to filling out the periodic table of elements without the aid of quantum mechanics to explain its patterns.

There is a rich history of physicists quickly turning to cosmology after learning something novel about black holes. The story has often been the same: we've been defeated and humbled, but after licking our wounds, we've returned to learn more from what black holes have to teach us. In this instance, the depth of what we've realized about black holes and the breadth of interest in quantum cosmology from scientists around the world may tell a different tale. SA

Edgar Shaghoulian is an assistant professor of physics at the University of California, Santa Cruz. His work focuses on black holes and quantum cosmology.

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Extreme Quantum Correlations

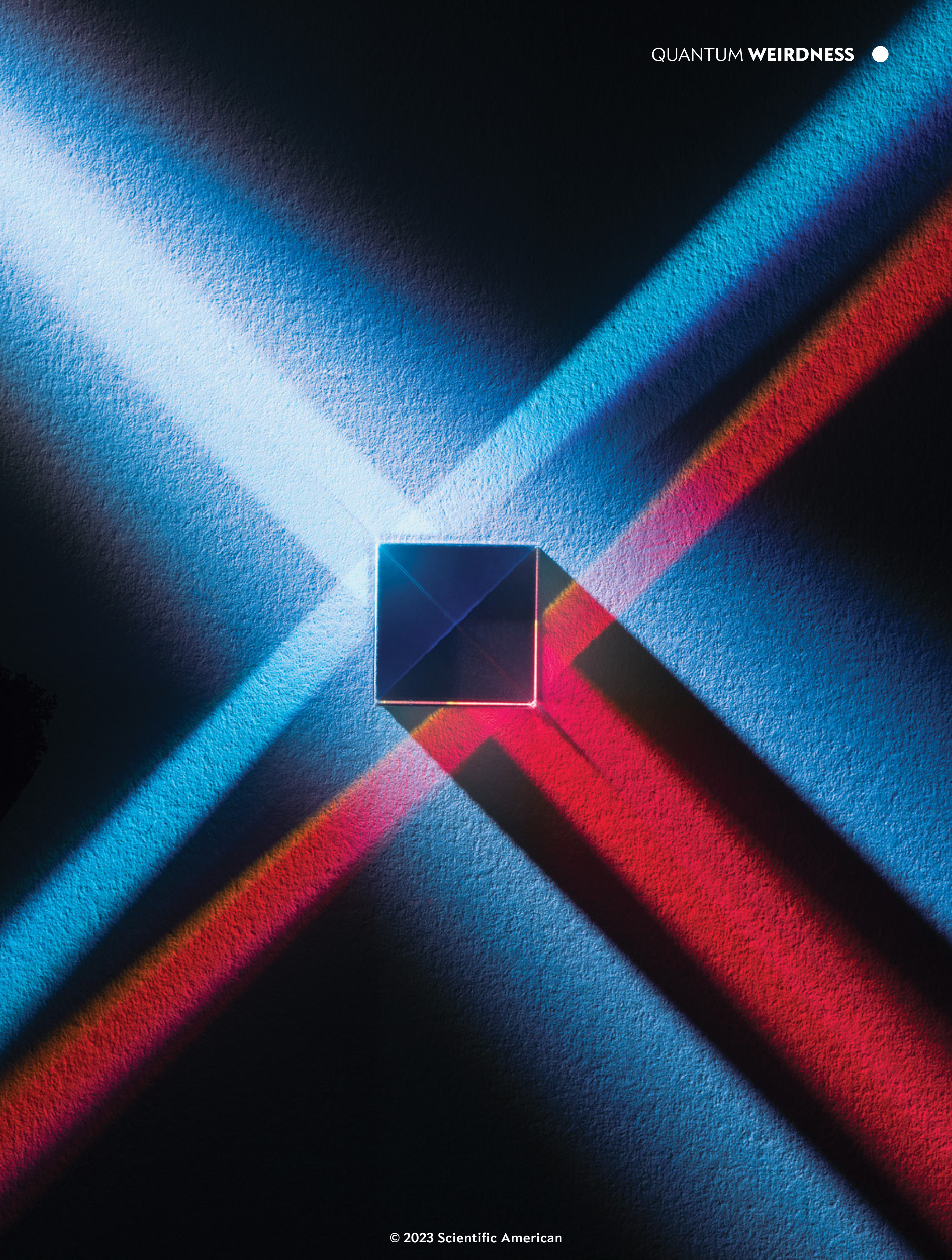
A playful demonstration of quantum pseudotelepathy could lead to advances in communication and computation

By Philip Ball

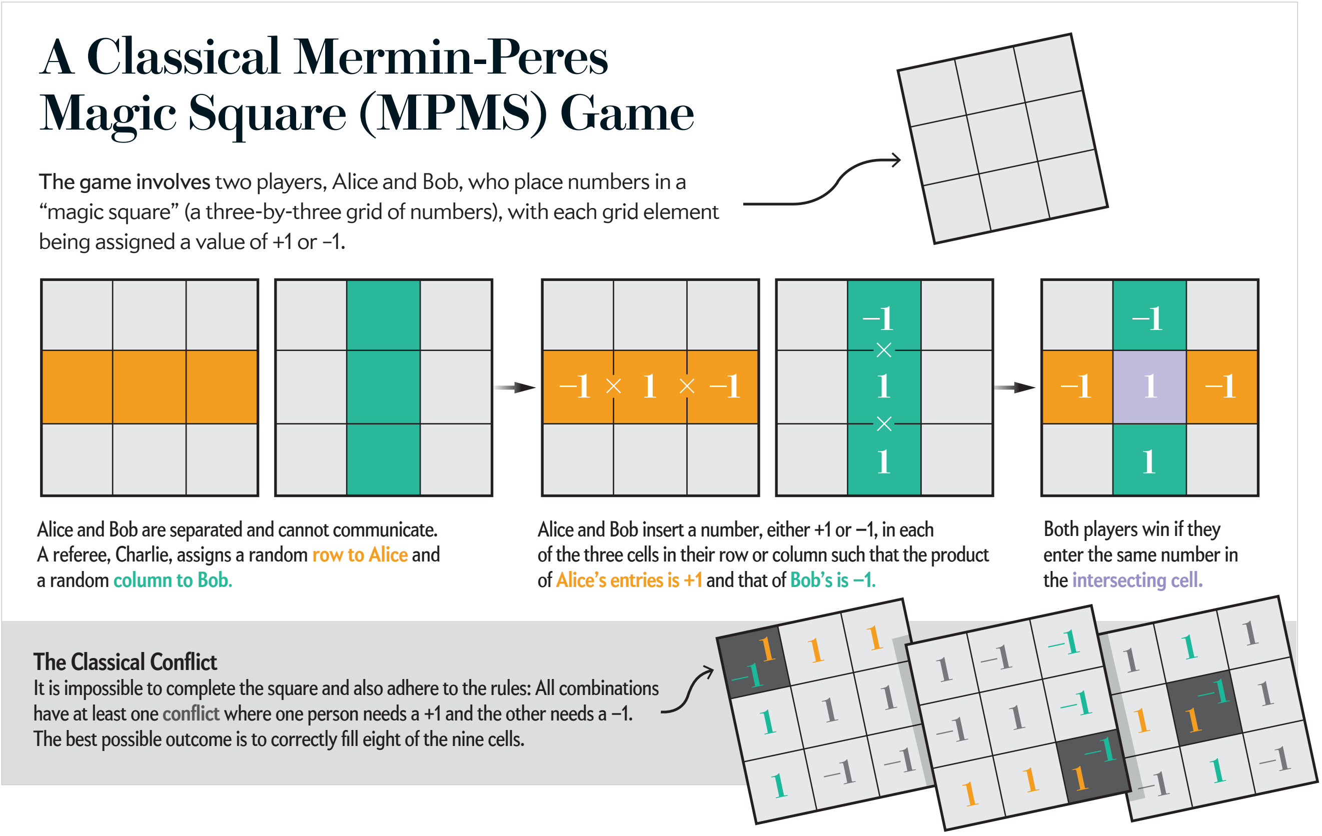
TO WIN AT THE CARD GAME OF BRIDGE, WHICH is played by two sets of partners, one player must somehow signal to their teammate the strength of the hand they hold. Telepathy would come in handy here. But telepathy isn't real, right?

That's correct. For decades, however, physicists suspected that if bridge were played using cards governed by the rules of quantum mechanics, something that looks uncannily like telepathy should be possible. Now researchers in China have experimentally demonstrated this so-called quantum pseudotelepathy—not in quantum bridge but in a two-player quantum competition called the Mermin-Peres magic square (MPMS) game, where winning requires that the players coordinate their actions without exchanging information with each other. Used judiciously, quantum pseudotelepathy allows the players to win each and every round of the game—a flawless performance that would otherwise be impossible. The experiment, conducted using laser photons, probes the limits of what quantum mechanics permits in allowing information to be shared between particles.

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The work "is a beautiful and simple direct implementation of the Mermin-Peres magic square game," says Arul Lakshminarayan of the Indian Institute of Technology Madras, who was not involved in the experimental demonstration. Its beauty, he adds, comes in part from its elegance in confirming that a quantum system's state is not well defined prior to actual measurement—something often considered to be quantum mechanics' most perplexing trait. "These quantum games seriously undermine our common notion of objects having preexisting properties that are revealed by observations," he says.

Two quantum physicists, Asher Peres and David Mermin, independently devised the MPMS in 1990. It involves two players (called Alice and Bob, as is tradition in quantum-mechanical thought experiments) who have to fill in a "magic square"—a three-by-three grid of numbers—with each grid element being assigned a value of +1 or −1. In each round, a referee (Charlie) sends at random a row to Alice and subsequently a column to Bob (there are nine such row-and-column combinations). The players have to tell Charlie which values of +1 or −1 to put in their three grid spaces. As with any magic-square challenge (such as Sudoku), the sums of each row and column must meet particular constraints: here the product of all the entries in a row must equal +1, and the product of all the columns must be −1. Alice and Bob win a round if they both assign the same value to the grid element where the column and row overlap.

Classically it's impossible to win all rounds because even if Alice and Bob guess well each time, there is inevitably one round for every completed square where their assignations must conflict. The best they can do is achieve eight wins out of every nine.

But now suppose that Alice and Bob can use this quantum strategy: Instead of assigning each grid element a value of +1 or −1, they assign it a pair of quantum bits (qubits), each of which has a value of +1 or −1 when measured. The value given by each player to a particular grid element is determined by measuring the two qubit values and finding the product of the pair. Now the classical conflict can be avoided because Alice and Bob can elicit different values from the same two qubits depending on how they make their measurements. There is a particular measurement strategy that will ensure the winning criteria for any given round—that the products of Alice's and Bob's three entries are +1 and −1, respectively—are met for all nine permutations of rows and columns.

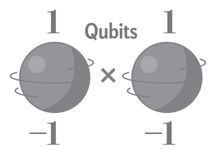
There's a wrinkle to this strategy, however. To make the right set of measurements, Alice and Bob need to know which of their three grid elements is the one that overlaps with the other player's—they need to coordinate. But in the MPMS, this is no problem, because they make their measurements sequentially on the same three qubit pairs. This means the pair that reaches Bob has an imprint of how Alice has already measured those qubits: they can transmit information to each other.

In 1993 Mermin showed that the MPMS could be used to demonstrate a quantum phenomenon called contextuality. First identified by Northern Irish physicist John Stewart Bell in 1966, contextuality refers to the fact that the outcome of a quantum measurement may depend on how the measurement is done. A set of classical measurements in a system will give the same results no matter what sequence those measurements are performed in. But for quantum measurements, this is not always so. In the MPMS, the contextuality arises from the fact that the mea-

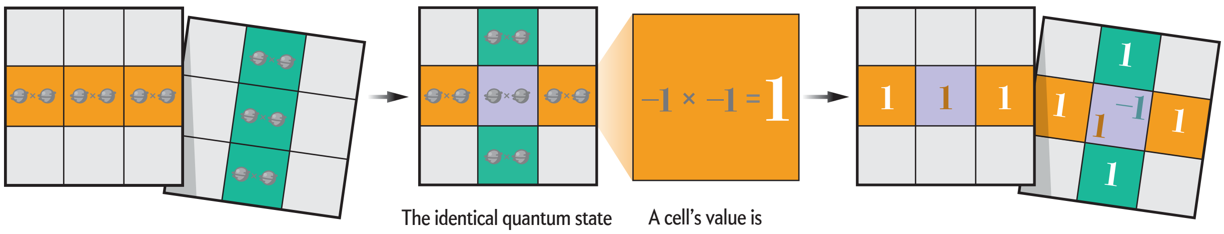
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A Quantum MPMS Game



It is possible to correctly fill out all nine cells by entering a pair of quantum bits (qubits) into each cell in lieu of a +1 or −1. The qubits are in superposition of +1 and −1, with each settling on either value when measured.



Charlie assigns a random row to Alice and a random column to Bob. Alice and Bob assign qubit pairs to each cell in their assigned row or column.

The identical quantum state of the qubit pairs in the intersecting cell satisfies the rule that Alice's and Bob's respective entries must match.

A cell's value is determined by measuring the two qubit values and finding their product.

The product of Alice's entries must be +1 and that of Bob's must be −1. Alice and Bob can elicit different values from the same two qubits. Knowing Alice's entry, Bob can make the right set of measurements to ensure a win.

surement for a given qubit pair may give a different result depending on which other two pairs are being measured, too.

But what if we forbid any communication in the MPMS by assigning Alice and Bob different qubit pairs and saying that they can't confer about how to measure them? Then each player can be guaranteed nine out of nine wins only if they make the right guesses about what the other player does. But in a study published in 2005, quantum theorist Gilles Brassard of the University of Montreal and his colleagues showed that the players can use quantum principles to guarantee a win in every round even without communicating by using what they called quantum pseudotelepathy.

This strategy involves entangling one qubit from each of the pairs sent to Alice or Bob with a corresponding qubit used by the other player. Entangled particles have correlated properties, so if Alice measures the value for her particle, the value for Bob's particle becomes fixed, too. Two entangled qubit particles could be anticorrelated such that if Alice's qubit is found to have a value of +1, Bob's must be −1. There is no way to know which value Alice's qubit has before it is measured—it could be +1 or −1. But Bob's will always be its opposite. More important, a property entangled between pairs of particles is said to be "nonlocal," meaning it is not "local" to either particle but rather shared between the two. Even if the particles are separated by vast distances, the entangled pair must be regarded as a single, nonlocal object. The same basic idea for winning a quantum game was proposed in 2001 by quantum theorist Adán Cabello of the University of Seville in Spain in a game he called "all or nothing," which was later shown to be equivalent to the nonlocal (pseudotelepathic) MPMS.

Some researchers regard entanglement as the most fundamental aspect of quantum mechanics. It implies a kind of information sharing between particles. That's the key to leveraging entanglement for quantum pseudotelepathy: Alice and Bob don't have to exchange information to coordinate their actions, because the necessary information is already shared in the pairs of particles themselves.

Both contextuality and nonlocality provide "quantum resources" that can be used to gain some advantage over classical approaches to information processing. In quantum computing, for example, entanglement between the quantum bits is generally the resource that creates a shortcut to a solution to the problem unavailable to a classical computer.

Physicists have repeatedly demonstrated Cabello's all-or-nothing game in the real world using entangled photons. But while those experiments established how entanglement could convey a "quantum advantage" by beating classical performance, Kai Chen of the University of Science and Technology of China, Xi-Lin Wang of Nanjing University in China and their colleagues devised a new experiment that they say implements the full protocol to achieve a guaranteed win in every round—genuine, consistent quantum pseudotelepathy.

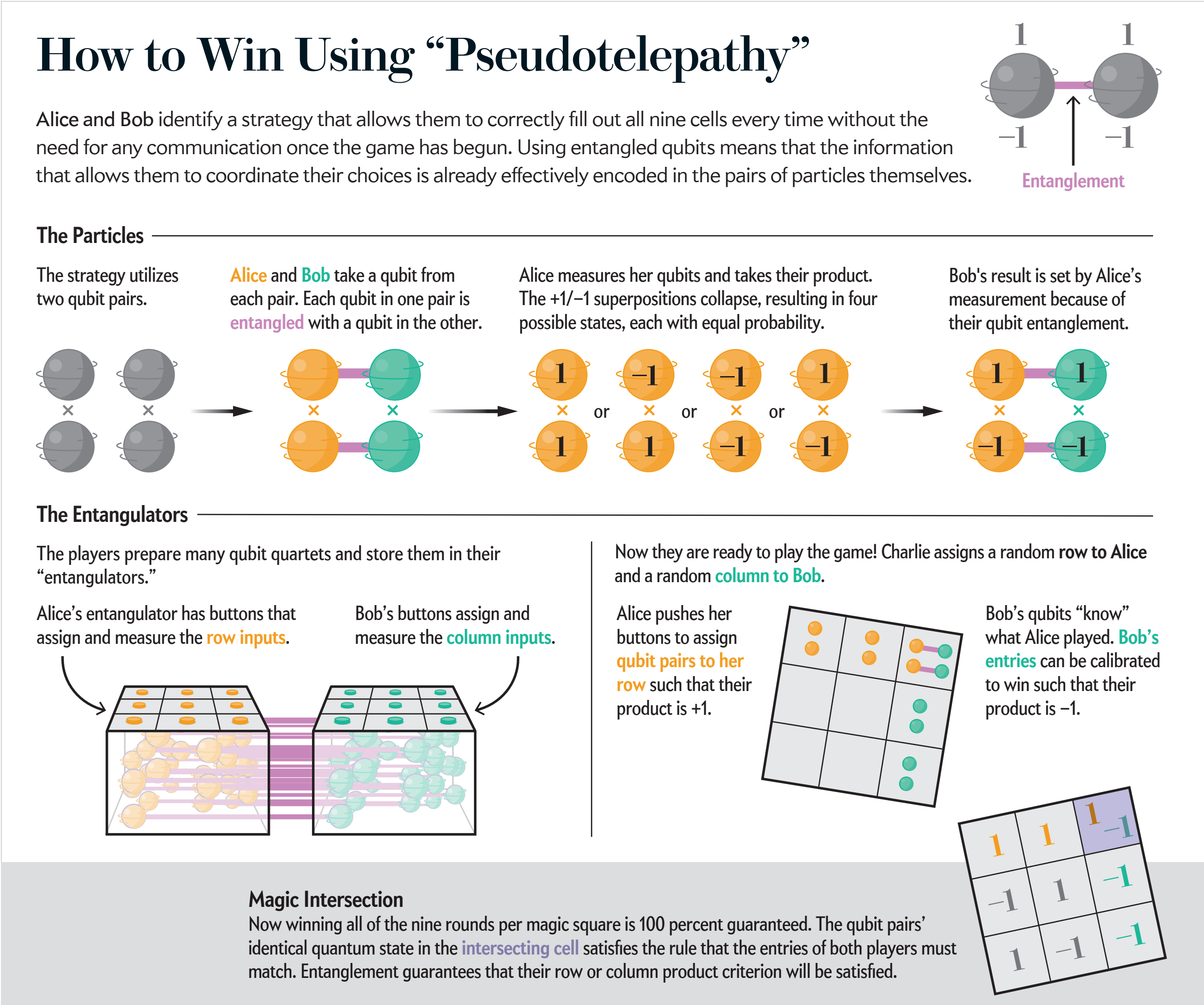
Ideally, Alice and Bob would prepare many sets of four qubits before the game starts, each quartet consisting of two entangled pairs. Alice would get one of each of these pairs, and Bob would receive the other. Making two entangled pairs of photons for each round of the game is immensely challenging, however, the researchers say. For one thing, the production of even a single entangled pair happens only with low probability in their apparatus, so making two at once would be extremely unlikely. And detecting two pairs at once, as the pseudotelepathic MPMS demands, is more or less impossible for this optical implementation.

Instead Chen, Wang and their colleagues prepared single-photon pairs and entangled two of their properties independently: their polarization state and a property called orbital angular momentum. The photons were contained in ultrashort laser pulses lasting just 150 femtoseconds and were entangled by passage through two so-called nonlinear optical crystals. A thin slab of barium borate first split a single photon into two photons of lower energy with correlated angular momenta. They were then entangled via their polarization, too, by being sent through a crystal of a yttrium-vanadium compound.

To demonstrate a nearly 100 percent success rate, the researchers needed to improve their detection efficiency so that almost none of the entangled photons escaped unseen. Even then the theoretical limit couldn't be reached precisely in the experi-

Graphics by Lucy Reading-Ikkanda

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ment—but the researchers were able to show they could win every round with between 91.5 and 97 percent probability. This range translates to reliably beating the classical eight-out-of-nine limit in 1,009,610 rounds out of a total of 1,075,930 played.

The pseudotelepathic MPMS game exploits the strongest degree of correlation between particles that quantum mechanics can possibly provide, Chen says. "Our experiment probes how to generate extreme quantum correlations between particles," he says. If these correlations were any stronger, they would imply faster-than-light information exchange that a host of other independent experiments indicate is impossible.

Mermin says that although it's experimentally impressive, this success reveals nothing beyond the fact that quantum mechanics works as we thought. Cabello does not entirely agree. Above and beyond being an experimental tour de force, he says, the work shows a new wrinkle in what quantum rules make possible by mobilizing two sources of quantum advantage at the same time: one linked to nonlocality and the other linked to contextuality. Investigating the two effects simultaneously, Cabello says, should allow physicists to more rigorously explore the connections between them.

What's more, each of these resources could in principle be put to different uses in quantum processing, boosting its versatility. "For example, nonlocality can be used for secret communication [using quantum cryptography] while contextuality can be used for quantum computation," Cabello says. In this scenario, Bob could, for instance, set up secure communication with Alice while at the same time performing a computation with Charlie faster than classical methods permit.

The use of shared entanglement in these experiments "leads to effects that seem classically magical," Lakshminarayan says. But given how often quantum mechanics is misused as a bogus justification for pseudoscientific claims, is it perhaps asking for trouble to call the phenomenon "pseudotelepathy"? It is "a bad term inviting nonsensical interpretations," Mermin says. But although Cabello agrees, he recognizes that evocative names can help advertise the interest of the phenomenon. "Let's not kid ourselves," he says. "It is probably thanks to the word 'pseudotelepathy' that [you and I] are having this conversation." SA

Philip Ball is a science writer based in London. His next book, *How Life Works* (University of Chicago Press), will be published in the fall of 2023.

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That Elusive Quantum Glow

Once considered practically unseeable, a phenomenon called the Unruh effect might soon be revealed in laboratory experiments

By Joanna Thompson

THEORETICAL PHYSICS IS FULL OF WEIRD AND WONDERFUL CONCEPTS: WORMHOLES, quantum foam and multiverses, just to name a few. The problem is that although such things easily emerge from theorists' equations, they are practically impossible to create and test in a laboratory setting. But for one such "untestable" theory, an experimental setup might be just on the horizon.

Researchers at the Massachusetts Institute of Technology and the University of Waterloo in Ontario say they've found a way to test the Unruh effect, a bizarre phenomenon predicted to arise from objects moving through empty space. If scientists are able to observe the effect, the feat could confirm some long-held assumptions about the physics of black holes. Their proposal was published in *Physical Review Letters* in April 2022.

If you could observe the Unruh effect in person, it might look a bit like jumping to hyperspace in the *Millennium Falcon*—a sudden rush of light bathing your view of an otherwise black void. As an object accelerates in a vacuum, it becomes swaddled in a warm cloak of glowing particles. The faster the acceleration, the warmer the glow. "That's enormously strange" because a vacuum is supposed to be empty by definition, explains quantum physicist Vivishek Sudhir of M.I.T., one of the study's co-authors. "You know, where did this come from?"

Where it comes from has to do with the fact that so-called empty space is not exactly empty at all but rather suffused by overlapping energetic quantum fields. Fluctuations in these fields can give rise to photons, electrons, and other particles and can be sparked by an accelerating body. In essence, an object speeding through a field-soaked vacuum picks up a fraction of the fields' energy, which is subsequently reemitted as Unruh radiation.

The effect takes its name from the theoretical physicist William G. Unruh, who described his eponymous phenomenon in 1976. But two other researchers—mathematician Stephen A. Fulling and physicist Paul Davies—worked out the formula independently within three years of Unruh (in 1973 and 1975, respectively).

"I remember it vividly," says Davies, who is now a Regents Professor at Arizona State University. "I did the calculations sitting at my wife's dressing table because I didn't have a desk or an office."

A year later Davies met Unruh at a conference where Unruh was giving a lecture about his recent breakthrough. Davies was surprised to hear Unruh describe a phenomenon very similar to what had emerged from his own dressing-table calculations. "And so we got together in the bar afterward," Davies recalls. The two quickly struck up a collaboration that continued for several years.

Davies, Fulling and Unruh all approached their work from a purely theoretical standpoint; they never expected anyone to design a real-world experiment around it. As technology advances, however, ideas that were once relegated to the world of theory, such as gravitational waves and the Higgs boson, can come within reach of actual observation. And observing the Unruh effect, it turns out, could help cement another far-out physics concept.

"The reason people are working on the Unruh effect is not because they think that accelerated observers are so important," says Christoph Adami, a professor of physics, astronomy, molecular genetics and mi-

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crobiology at Michigan State University, who was not involved in the research. "They are working on this because of the direct link to black hole physics."

Basically, the Unruh effect is the flip side of a far more famous physics phenomenon: Hawking radiation, named for the late physicist Stephen Hawking, who theorized that an almost imperceptible halo of light should leak from black holes as they slowly evaporate.

In the case of Hawking radiation, that warm, fuzzy effect is essentially a result of particles being pulled into a black hole by gravity. But for the Unruh effect, it's a matter of acceleration—which is, per Einstein's equivalence principle, gravity's mathematical equal.

Imagine you are standing in an elevator. With a jolt, the car rushes up to the next floor, and for a moment you feel yourself pulled toward the floor. From your viewpoint, "that is essentially indistinguishable from Earth's gravity suddenly being turned up," Sudhir says.

The same holds true, he says, from a math perspective. "It's as simple as that: there is an equivalence between gravity and acceleration," Sudhir adds.

Despite its theoretical prominence, scientists have yet to observe the Unruh effect. (They haven't managed to see Hawking radiation, either.) That's because the Unruh effect has long been considered extraordinarily difficult to test experimentally. Under most circumstances, researchers would need to subject an object to ludicrous accelerations—upward of 25 *quintillion* times the force of Earth's gravity—to produce a measurable emission. Alternatively, more accessible accelerations might be used—but in that case, the probability of generating a detectable effect would be so low that such an experiment would need to run continuously for billions of years to yield a useful result. Sudhir and his co-authors, however, believe that they have found a loophole.

By grabbing hold of a single electron in a vacuum with a magnetic field, then accelerating it through a carefully configured bath of photons, the researchers realized that they could "stimulate" the particle, artificially bumping it up to a higher energy state. This added energy multiplies the effect of acceleration, which means that, using the electron itself as a sensor, researchers could pick out Unruh radiation surrounding the particle without having to apply so many g-forces (or having to wait for eons).



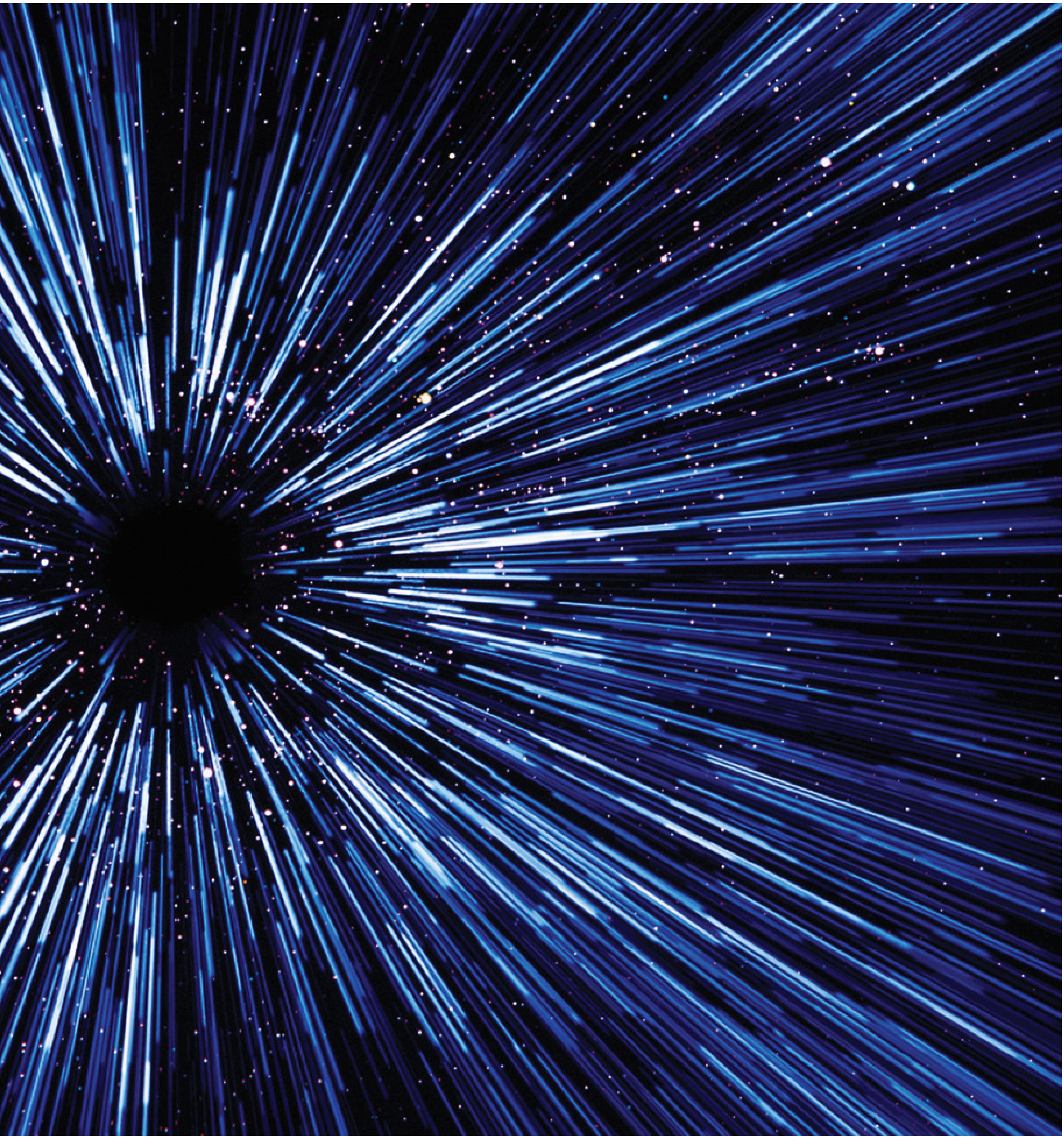
ACCORDING TO a predicted phenomenon known as the Unruh effect, an accelerating object, such as a starship traveling at close to the speed of light, should generate showers of faintly glowing particles.

DigitalArt/Getty Images

Unfortunately, an energy-boosting photon bath also adds background "noise" by amplifying other quantum-field effects in the vacuum. "That's exactly what we don't want to happen," Sudhir says. But by carefully controlling the trajectory of the electron, the experimenters should be able to nullify this potential interference—a process Sudhir likens to throwing an invisibility cloak over the particle.

And unlike the kit required for most other cutting-edge particle physics experiments, such as the giant superconducting magnets and sprawling beamlines of the Large Hadron Collider at CERN near Geneva, the researchers say their Unruh effect simulation could be set up in most university labs. "It doesn't have to be some

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huge experiment," says paper co-author Barbara Šoda, a postdoctoral researcher at the Perimeter Institute for Theoretical Physics in Ontario. In fact, Sudhir and his Ph.D. students began work on designs for a version meant to actually be built.

Adami sees the new research as an elegant synthesis of several different disciplines, including classical physics, atomic physics and quantum-field theory. "I think this paper is correct," he says. But much like the Unruh effect itself, "to some extent, it's clear that this calculation has been done before."

For Davies, the potential to test the effect could open up exciting new doors for both theoretical and applied physics, further validating nigh-unobservable phenomena predicted by theorists while expanding the tool kit experimentalists can use to interrogate nature. "The thing about physics that makes it such a successful discipline is that experiment and theory very much go hand in hand," he says. "The two are in lockstep." Testing the Unruh effect promises to be a pinnacle achievement for both. SA

Joanna Thompson is an insect enthusiast and former *Scientific American* intern. She is based in New York City.

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Spin Paradox

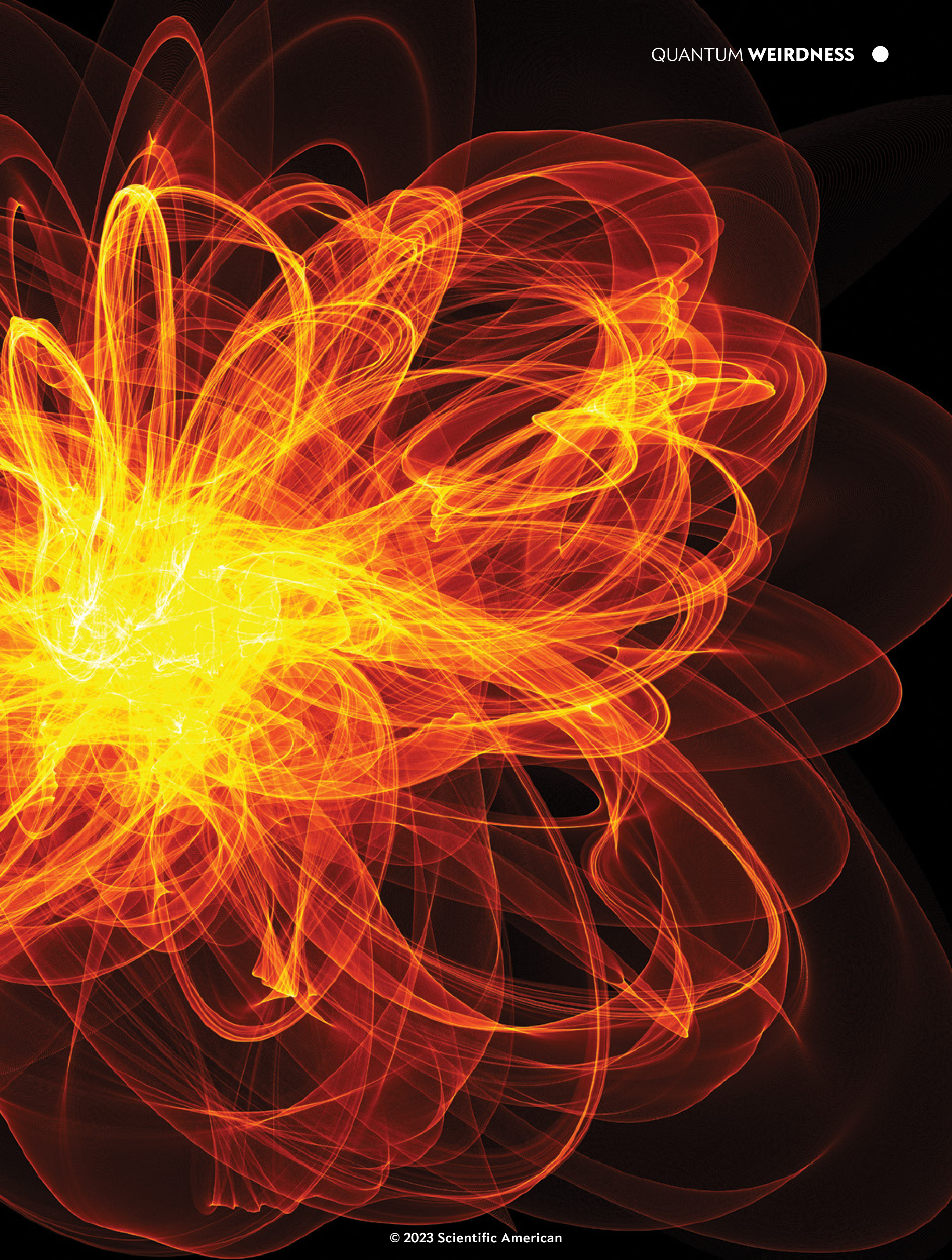
Quantum particles aren't spinning, so where does their spin come from?

By Adam Becker

ELECTRONS ARE PROFICIENT LITTLE magicians. They seem to flit about an atom without tracing a particular path, they frequently appear to be in two places at once, and their behavior in silicon microchips powers the computing infrastructure of the modern world. But one of their most impressive tricks is deceptively simple, like all the best magic. Electrons always seem to spin. Every electron ever observed, whether it's just ambling around a carbon atom in your fingernail or speeding through a particle accelerator, looks like it's constantly doing tiny pirouettes as it makes its way through the world. Its spinning never appears to slow or speed up. No matter how an electron is jostled or kicked, it always looks like it's spinning at exactly the same speed. It even has a little magnetic field, just like a spinning object with electric charge should. Naturally, physicists call this behavior "spin."

THE FACT that electrons have the quantum property of spin is essential to the world as we know it. Yet physicists don't think the particles are actually spinning.

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But despite appearances, electrons don't spin. They can't spin; proving that it's impossible for electrons to be spinning is a standard homework problem in any introductory quantum physics course. If electrons actually spun fast enough to account for all of the spinlike behavior they display, their surfaces would be moving much faster than the speed of light (if they even have surfaces at all). Even more surprising is that for nearly a century, this seeming contradiction has been written off by most physicists as just one more strange feature of the quantum world—nothing to lose sleep over.

Yet spin is deeply important. If electrons didn't seem to spin, your chair would collapse down to a minuscule fraction of its size. You'd collapse, too—and that would be the least of your problems. Without spin, the entire periodic table of elements would come crashing down, and all of chemistry would go with it. In fact, there wouldn't be any molecules at all. So spin isn't just one of the best tricks that electrons pull; it's also one of their most crucial. And like any good magician, electrons haven't told anyone how the trick is done. But now a new account of spin may be on the horizon—one that pulls back the curtain and shows how the magic works.

> If electrons didn't seem to spin, your chair would collapse down to a minuscule fraction of its size. You'd collapse, too—and that would be the least of your problems.

A DIZZYING DISCOVERY

SPIN HAS ALWAYS been confusing. Even the first people to develop the idea of spin thought it had to be wrong. In 1925 two young Dutch physicists, Samuel Goudsmit and George Uhlenbeck, were puzzling over the latest work from famous (and famously acerbic) physicist Wolfgang Pauli. Pauli, in an attempt to explain the structure of atomic spectra and the periodic table, had recently postulated that electrons had a "two-valuedness not describable classically." But Pauli hadn't said what physical property of the electron his new value corresponded to, and Goudsmit and Uhlenbeck wondered what it could be.

All they knew—all anyone knew at the time—was that Pauli's new value was associated with discrete units of a well-known property from classical Newtonian physics called angular momentum. Angular momentum is just the tendency for a rotating thing to continue rotating. It's what keeps tops spinning and bicycles upright. The faster an object is rotating, the more angular momentum it has, but the shape and mass of the object both matter, too. A heavier object has more angular momentum than a lighter object spinning just as fast, and a spinning object with more mass at its edges has more angular momentum than it would if its mass were clumped at its center.

Objects can have angular momentum without spinning. Any thing revolving around another thing—Earth going around the sun or a set of keys swinging around your finger on a lanyard—has some angular momentum. But Goudsmit and Uhlenbeck knew that this kind of angular momentum could not be the source of Pauli's new number. Electrons do appear to move around the atomic nucleus, held close by the attraction between their negative electrical charge and the positive pull of the protons in the nucleus. But the angular momentum that they have from this movement was already well accounted for and could not be Pauli's new number. The physicists also knew that there were already three numbers associated with the electron, which corresponded to the three dimensions of space it could move in. A fourth number meant a fourth way the electron could move. The only option, the two young physicists reasoned, was for the electron itself to be spinning, like Earth rotating on its axis as it orbits the sun. If electrons could spin in one of two directions—clockwise or counterclockwise—that would account for Pauli's "two-valuedness."

Excitedly, Goudsmit and Uhlenbeck wrote up their new idea and showed it to their mentor, Paul Ehrenfest. Ehrenfest, a close friend of Albert Einstein and a formidable physicist in his own right, thought the idea was intriguing. While he considered it, he told the two eager young men to go consult with someone older and wiser: Hendrik Antoon Lorentz, the grand old man of Dutch physics, who had anticipated much of the development of special relativity two decades earlier and whom Einstein himself held in the highest regard.

But Lorentz was less impressed with the idea of spin than Ehrenfest. As he pointed out to Uhlenbeck, the electron was known to be very small, at least 3,000 times smaller than an atom—and atoms were already known to be about a tenth of a nanometer across, a million times smaller than the thickness of a sheet of paper. With the electron so small, and with its even smaller mass—a billionth of a billionth of a billionth of a gram—there was no way it could possibly be spinning fast enough to account for the angular momentum Pauli and others were searching for. In fact, as Lorentz told Uhlenbeck, the surface of the electron would have to be moving 10 times faster than the speed of light, a flat impossibility.

Defeated, Uhlenbeck went back to Ehrenfest and told him the news. He asked Ehrenfest to scrap the paper, only to be told that it was too late—his mentor had already sent the paper off to be published. "You are both young enough to be able to afford a stupidity," Ehrenfest said. And he was right. Despite the fact that the electron couldn't be spinning, the idea of spin was widely accepted as correct—just not in the usual way. Rather than an electron actually spinning, which was impossible, physicists interpreted the finding as meaning that the electron carried with it some intrinsic angular momentum, as if it were spinning, even though it couldn't be. Nevertheless, the idea was still called "spin," and Goudsmit and Uhlenbeck were widely hailed as the progenitors of the idea.

Spin proved to be crucial in explaining fundamental properties of matter. In the same paper where he had suggested his new two-valued number, Pauli had also suggested an "exclusion principle," the notion that no two electrons could occupy the exact same state. If they could, then every electron in an atom would just fall to the lowest energy state, and virtually all elements would behave in almost exactly the same way as one

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another, destroying chemistry as we know it. Life wouldn't exist. Water wouldn't exist. The universe would simply be full of stars and gas drifting through a boring and indifferent cosmos without encountering so much as a rock. In fact, as was later realized, solid matter of any kind would be unstable. Although Pauli's idea was clearly correct, it was unclear why electrons couldn't share states. Understanding the origin of Pauli's exclusion principle would unlock explanations for all of these deep facts of quotidian life.

The answer to the puzzle was in spin. Spin was soon discovered to be a basic property of all fundamental particles, not just electrons—and one with a deep connection to the behavior of those particles in groups. In 1940 Pauli and Swiss physicist Markus Fierz proved that when quantum mechanics and Einstein's special relativity were combined, it led inevitably to a connection between spin and group statistical behavior. Pauli's exclusion principle was merely a special case of this spin-statistics theorem, as it came to be known.

The theorem is a "mighty fact about the world," says emeritus physics professor Michael Berry of the University of Bristol in England. "It underlies chemistry. It underlies superconductivity. It's a very fundamental fact." And like so many fundamental facts in physics, spin was found to be technologically useful as well. In the second half of the 20th century, spin was harnessed to develop lasers, explain the behavior of superconductors and point the way to building quantum computers.

SEEING PAST THE SPIN

BUT ALL OF THESE fabulous discoveries, applications and explanations still leave Goudsmit and Uhlenbeck's question on the table: What is spin? If electrons must have spin but can't be spinning, then where does that angular momentum come from? The standard answer is that this momentum is simply inherent to subatomic particles and doesn't correspond to any macroscopic notion of spinning.

Yet this answer is not satisfying to everyone. "I never loved the account of spin that you got in a quantum mechanics class," says Charles Sebens, a philosopher of physics at the California Institute of Technology. "You're introduced to it, and you think, 'Well, that's strange. They act like they spin, but they don't really spin? Okay. I guess I can learn to work with that.' But it's odd."

Recently, however, Sebens has had an idea. "Within quantum mechanics, it seems like the electron is not rotating," he proposes. But, he adds, "quantum mechanics is not our best theory of nature. Quantum field theory is a deeper and more accurate theory."

Quantum field theory is where the quantum world of subatomic particles meets the most famous equation in the world: $E = mc^2$, which encapsulates Einstein's discovery that matter can turn into energy and vice versa. (Quantum field theory is also what gives rise to the spin-statistics theorem.) Because of this ability, when subatomic particles interact, new particles are often created out of their energy, and existing particles can decay into something else. Quantum field theory handles this phenomenon by describing particles as arising out of fields that pervade all of spacetime, even empty space. These fields allow particles to appear and disappear, all in accordance with both the strict dictates of Einstein's special relativity and the probabilistic laws of the quantum world.

And it's these fields, according to Sebens, that may contain the solution to the puzzle of spin. "The electron is ordinarily thought of as a particle," he says. "But in quantum field theory, for every particle, there's a way of thinking about it as a field." In particular, the electron can be thought of as an excitation in a quantum field known as the Dirac field, and this field may be what carries the spin of the electron. "There's a real rotation of energy and charge in the Dirac field," Sebens says. If this is where the angular momentum resides, the problem of an electron spinning faster than the speed of light vanishes; the region of the field carrying an electron's spin is far larger than the purportedly pointlike electron itself. Therefore, Sebens asserts, in a way, Pauli and Lorentz were half-right: there isn't a spinning particle. There's a spinning field, and that field is what gives rise to particles.

AN UNANSWERABLE QUESTION?

SO FAR SEBENS'S IDEA has made ripples, not waves. When it comes to whether electrons are spinning, "I don't think it's an answerable question," says Mark Srednicki, a physicist at the University of California, Santa Barbara. "We're taking a concept that originated in the ordinary world and trying to apply it to a place where it doesn't really apply anymore. So I think it's really just a matter of choice or definition or taste whether you want to say the electron is really spinning." Hans Ohanian, a physicist at the University of Vermont who has done other work on electron spin, points out that Sebens's original version of his idea doesn't work for antimatter.

But not all physicists are so dismissive. "The conventional formulation of how we think about spin is leaving something out potentially important," says Sean Carroll, a physicist at Johns Hopkins University and the Santa Fe Institute. "Sebens is very much on the right track, or at least he is doing something very, very useful in the sense that he's taking the 'fieldness' of quantum field theory very seriously." Still, Carroll points out, "physicists are, at heart, pragmatists.... If Sebens is 100 percent right, the physicists are going to say, 'Okay, what does that get me?'"

Doreen Fraser, a philosopher of quantum field theory at the University of Waterloo in Canada, echoes this point. "I'm open to this project that Sebens has of wanting to drill deeper into having some sort of physical intuition to go with spin," she says. "You have this nice mathematical representation; you want to have some intuitive physical picture to go along with it." Plus, a physical picture might also lead to new theories or experiments that hadn't occurred before. "To me, that would be the test of whether this is a good idea."

It's too early to say whether Sebens's work will bear this kind of fruit. And although he has written a paper about how to resolve Ohanian's concern regarding antimatter, there are other, related questions still remaining. "There's a lot of reasons to like" the field idea, Sebens says. "I take this more as a challenge than a knockdown argument against it." SA

Adam Becker is a freelance science journalist and author of *What Is Real?,* which is about the sordid untold history of quantum physics. He has written for the *New York Times,* the BBC, NPR, and elsewhere. He holds a Ph.D. in cosmology from the University of Michigan.

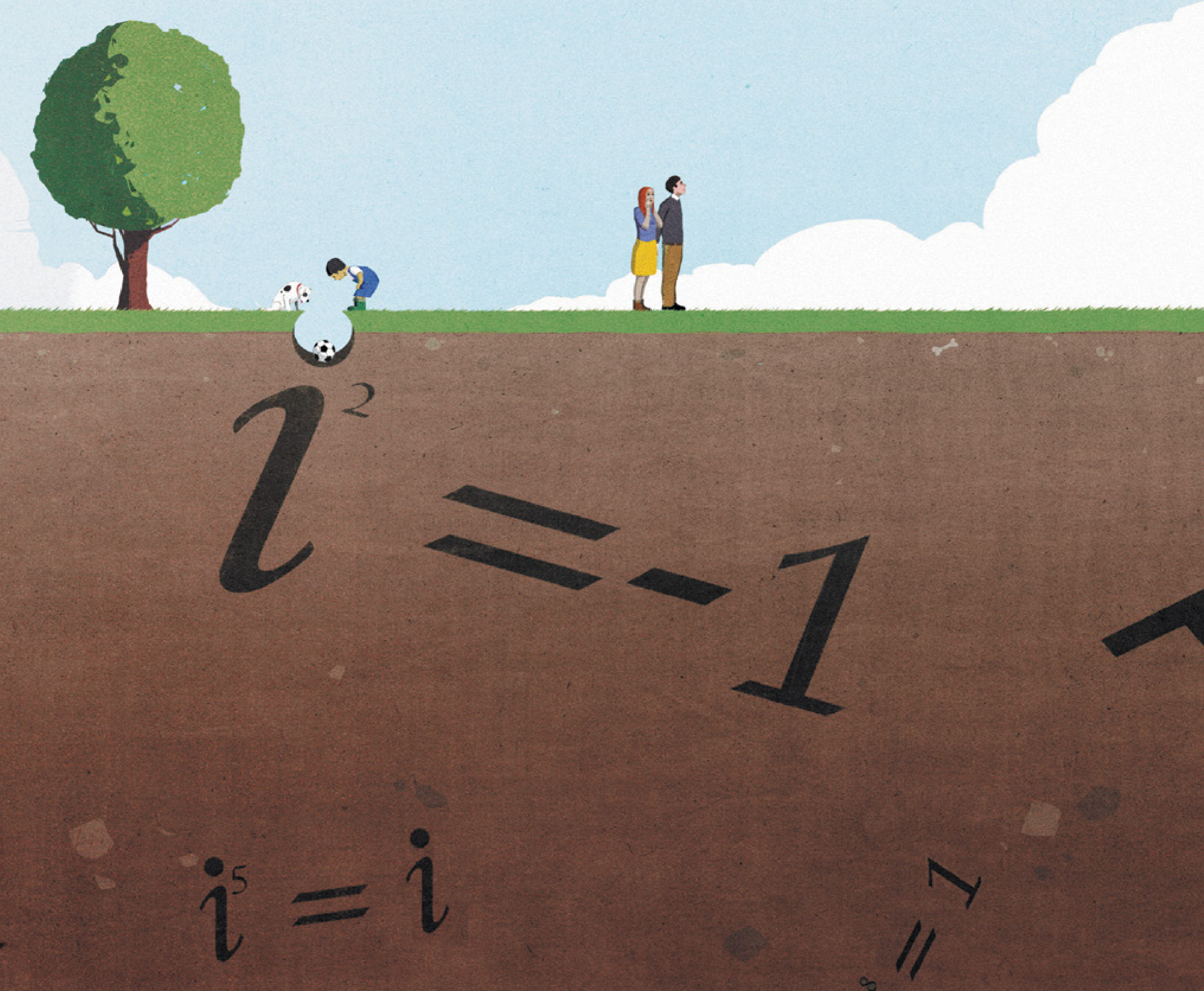
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Imaginary Uni

Complex numbers are an inescapable part of standard quantum theory

By Marc-Olivier Renou, Antonio Acín and Miguel Navascués

Illustration by Andrea Ucini



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IN 2020 ONE OF US, TONI, ASKED ANOTHER OF US, MARCO, TO COME TO HIS OFFICE at the Institute of Photonic Sciences, a large research center in Castelldefels near Barcelona. "There is a problem that I wanted to discuss with you," Toni began. "It is a problem that Miguel and I have been trying to solve for years." Marco made a curious face, so Toni posed the question: "Can standard quantum theory work without imaginary numbers?"

Imaginary numbers, when multiplied by themselves, produce a negative number. They were first named "imaginary" by philosopher René Descartes, to distinguish them from the numbers he knew and accepted (now called the real numbers), which did not have this property. Later, complex numbers, which are the sum of a real and an imaginary number, gained wide acceptance by mathematicians because of their usefulness for solving complicated mathematical problems. They aren't part of the equations of any fundamental theory of physics, however—except for quantum mechanics.

The most common version of quantum theory relies on complex numbers. When we restrict the numbers appearing in the theory to the real numbers, we arrive at a new physical theory: real quantum theory. In the first decade of the 21st century, several teams showed that this "real" version of quantum theory could be used to correctly model the outcomes of a large class of quantum experiments. These findings led many scientists to believe that real quantum theory could model any quantum experiment. Choosing to work with complex instead of real numbers didn't represent a physical stance, scientists thought; it was just a matter of mathematical convenience.

Still, that conjecture was unproven. Could it be false? After that conversation in Toni's office, we started on a months-long journey to refute real quantum theory. We eventually came up with a quantum experiment whose results cannot be explained through real quantum models. Our finding means that imaginary numbers are an essential ingredient in the standard formulation of quantum theory: without them, the theory would lose predictive power. What does this mean? Does this imply that imaginary numbers exist in some way? That depends on how seriously one takes the notion that the elements of the standard quantum theory, or any physical theory, "exist" as opposed to their being just mathematical recipes to describe and make predictions about experimental observations.

THE BIRTH OF IMAGINARY NUMBERS

COMPLEX NUMBERS date to the early 16th century, when Italian mathematician Antonio Maria Fiore challenged professor Niccolò Fontana "Tartaglia" (the stutterer) to a duel. In Italy at that time, anyone could challenge a mathematics professor to a "math duel," and if they won, they might get their opponent's job. As a result, mathematicians tended to keep their discoveries to themselves, deploying their theorems, corollaries and lemmas only to win intellectual battles.

From his deathbed, Fiore's mentor, Scipione del Ferro, had given Fiore a formula for solving equations of the form $x^3 + ax = b$, also known as cubic equations. Equipped with his master's achievement, Fiore presented Tartaglia with 30 cubic equations and challenged him to find the value of x in each case.

Tartaglia discovered the formula just before the contest, solved the problems and won the duel. Tartaglia later confided his formula to physician and scientist Gerolamo Cardano, who promised never to reveal it to anyone. Despite his oath, though, Cardano came up with a proof of the formula and published it under his name. The complicated equation contained two square roots, so it was understood that, should the numbers within be negative, the equation would have no solutions, because there are no real numbers that, when multiplied by themselves, produce a negative number.

In the midst of these intrigues, a fourth scholar, Rafael Bombelli, made one of the most celebrated discoveries in the history of mathematics. Bombelli found solvable cubic equations for which the del Ferro-Tartaglia-Cardano formula nonetheless required computing the square root of a negative number. He then realized that, for all these examples, the formula gave the correct solution, as long as he pretended that there was a new type of number whose square equaled -1. Assuming that every variable in the formula was of the form $a + \sqrt{-1} \times b$, with a and b being "normal" numbers, the terms multiplying

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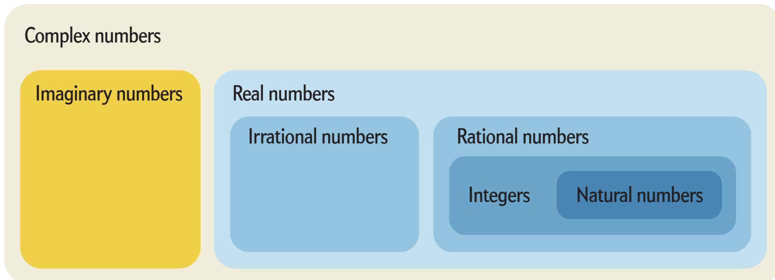
$\sqrt{-1}$ canceled out, and the result was the "normal" solution of the equation.

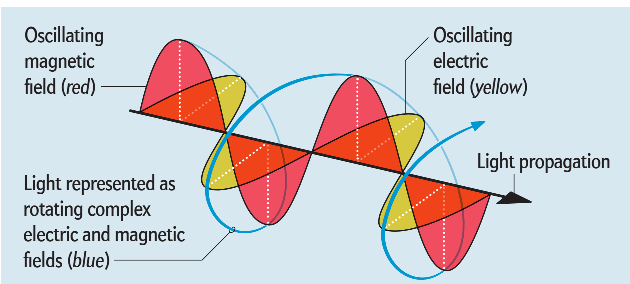
For the next few centuries mathematicians studied the properties of all numbers of the form $a + \sqrt{-1} \times b$, which were called "complex." In the 17th century Descartes, considered the father of rational sciences, associated these numbers with nonexistent features of geometric shapes. Thus, he named the number $i = \sqrt{-1}$ "imaginary," to contrast it with what he knew as the normal numbers, which he called "real." Mathematicians still use this terminology today.

Complex numbers turned out to be a fantastic tool, not only for solving equations but also for simplifying the mathematics of classical physics—the physics developed up until the 20th century. An example is the classical understanding of light. It is easier to describe light as rotating complex electric and magnetic fields than as oscillating real ones, despite the fact that there is no such thing as an imaginary electric field. Similarly, the equations that describe the behavior of electronic circuits are easier to solve if you pretend electric currents have complex values, and the same goes for gravitational waves.

What Are Imaginary Numbers?

"Imaginary" numbers are those that, when multiplied by themselves, produce a negative number. Complex numbers include both imaginary and real components. Real numbers include rational numbers (those that can be written as a ratio of two integers) and irrational numbers (those that can't be). Rational numbers include the integers (whole numbers and their negative counterparts, plus zero). Natural numbers are a subset of integers that include only the positive whole numbers.





Before the 20th century all such operations with complex numbers were simply considered a mathematical trick. Ultimately the basic elements of any classical theory—temperatures, particle positions, fields, and so on—corresponded to real numbers, vectors or functions. Quantum mechanics, a physical theory introduced in the early 20th century to understand the microscopic world, would radically challenge this state of affairs.

SCHRÖDINGER AND HIS EQUATION

IN STANDARD QUANTUM THEORY, the state of a physical system is represented by a vector (a quantity with a magnitude and direction) of complex numbers called the wave function. Physical properties, such as the speed of a particle or its position, correspond to tables of complex numbers called operators. From the start, this deep reliance on complex numbers went against deeply held convictions that physical theories must be formulated in terms of real magnitudes. Erwin Schrödinger, author of the Schrödinger equation that governs the wave function, was one of the first to express the general dissatisfaction of the physics community. In a letter to physicist Hendrik Lorentz on June 6, 1926, Schrödinger wrote, "What is unpleasant here, and indeed directly to be objected to, is the use of complex numbers. Ψ [the wave function] is surely fundamentally a real function."

At first, Schrödinger's uneasiness seemed simple to resolve: he rewrote the wave function, replacing a single vector of complex numbers with two real vectors. Schrödinger insisted this version was the "true" theory and that imaginary numbers were merely for convenience. In the years since, physicists have found other ways to rewrite quantum mechanics based on real numbers. But none of these alternatives has ever stuck. Standard quantum theory, with its complex numbers, has a convenient rule that makes it easy to represent the wave function of a quantum system composed of many independent parts—a feature that these other versions lack.

What happens, then, if we restrict wave functions to real numbers *and* keep the usual quantum rule for composing systems with many parts? At first glance, not much. When we demand that wave functions and operators have real entries, we end up with what physicists often call "real quantum theory." This theory is similar to standard quantum theory: if we lived in a real quantum world, we could still carry out quantum computations, send secret messages to one another by exchanging quantum particles, and teleport the physical state of a subatomic system over intercontinental distances.

All these applications are based on the counterintuitive features of quantum theory, such as superpositions, entanglement and the uncertainty principle, which are also part of real quantum theory. Because this formulation included these famed quantum features, physicists long assumed that the use of complex numbers in quantum theory was fundamentally a matter of convenience, and real quantum theory was just as valid as standard quantum theory. Back on that autumn morning in 2020 in Marco's office, however, we began to doubt it.

FALSIFYING REAL QUANTUM THEORY

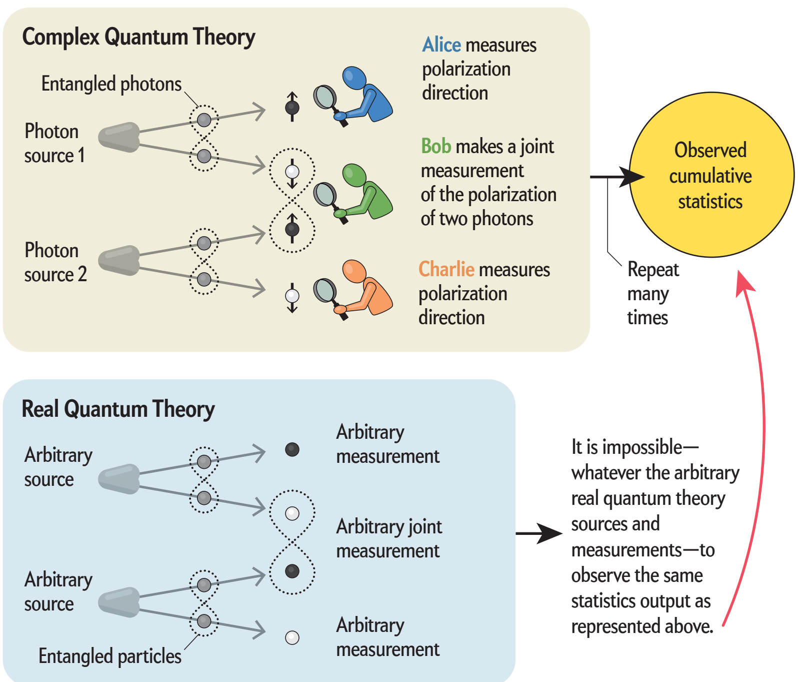
WHEN DESIGNING an experiment to refute real quantum theory, we couldn't make any assumptions about the experimental devices

Graphics by Jen Christiansen

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A Test of Two Theories

To test whether quantum theory requires complex numbers, physicists envisioned a thought experiment that was later carried out in actual laboratories. In this trial, two sources emit photons (particles of light) toward three observers: Alice, Bob and Charlie. The experiment, repeated many times, will produce statistics that are compatible only with the predictions of complex quantum theory, not with real quantum theory, the new theory obtained when scientists limit standard quantum theory to real numbers.



scientists might use, as any supporter of real quantum theory could always challenge them. Suppose, for example, that we built a device meant to measure the polarization of a photon. An opponent could argue that although we thought we measured polarization, our apparatus actually probed some other property—say, the photon's orbital angular momentum. We have no way to know that our tools do what we think they do. Yet falsifying a physical theory without assuming anything about the experimental setup sounds impossible. How can we prove anything when there are no certainties to rely on? Luckily, there was a historical precedent.

Despite being one of quantum theory's founders, Albert Einstein never believed our world to be as counterintuitive as the theory suggested. He thought that although quantum theory made accurate predictions, it must be a simplified version of a deeper theory in which its apparently paradoxical peculiarities would be resolved. For instance, Einstein refused to believe that Heisenberg's uncertainty principle—which limits how much can be known about a particle's position and speed—was fundamental. Instead he conjectured that the experimentalists of his time were not able to prepare particles with well-defined positions and speeds because of technological limitations. Einstein assumed that a future "classical" theory (one where the physical state of an elementary particle can be fully determined and isn't based on probabilities) would account for the outcomes of all quantum experiments.

We now know that Einstein's intuition was wrong because all such classical theories have been falsified. In 1964 John S. Bell showed that some quantum effects can't be modeled by any classical theory. He envisioned a type of experiment, now called a Bell test, that involves two experimentalists, Alice and Bob, who work in separate laboratories. Someone in a third location sends each of them a particle, which they measure independently. Bell proved that in any classical theory with well-defined properties (the kind of theory Einstein hoped would win out), the results of these measurements obey some conditions, known as Bell's inequalities. Then Bell proved that these conditions are violated in some setups in which Alice and Bob measure an entangled quantum state. The important property is that Bell's inequalities hold for all classical theories one can think of, no matter how convoluted. Therefore, their violation refuted all such theories.

Various Bell tests performed in labs since then have measured just what quantum theory predicts. In 2015 Bell experiments done in Delft, Netherlands, Vienna, Austria, and Boulder, Colo., finally did so while closing all the loopholes previous experiments had left open. Those results do not tell us that our world is quantum; rather they prove that, contra Einstein, it cannot be ruled by classical physics.

Could we devise an experiment similar to Bell's that would rule out quantum theory based on real numbers? To achieve this feat, we needed to envision a standard quantum theory experiment whose outcomes can't be explained by the mathematics of real quantum theory. We planned to first design a gedankenexperiment—a thought experiment—we hoped physicists would subsequently carry out in a lab. If it could be done, we figured, this test should convince even the most skeptical supporter that the world is not described by real quantum theory.

Our first, simplest idea was to try to upgrade Bell's original experiment to falsify real quantum theory, too. Unfortunately, two independent studies published in 2008 and 2009—one by Károly Pál and Tamás Vértesi and another by Matthew McKague, Michele Mosca and Nicolas Gisin—found this wouldn't work. The researchers were able to show that real quantum theory could predict the measurements of any possible Bell test just as well as standard quantum theory could. Because of their research, most scientists concluded that real quantum theory was irrefutable. But we and our co-authors proved this conclusion wrong.

DESIGNING THE EXPERIMENT

WITHIN TWO MONTHS of our conversation in Castelldefels, our little project had gathered eight theoretical physicists, all based

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there or in Geneva or Vienna. Although we couldn't meet in person, we exchanged e-mails and held online discussions many times a week. It was through a combination of long solitary walks and intensive Zoom meetings that on one happy day in November 2020 we came up with a standard quantum experiment that real quantum theory could not model. Our key idea was to abandon the standard Bell scenario, in which a single source distributes particles to several separate parties, and consider a setup with several independent sources. We had observed that, in such a scenario, which physicists call a quantum network, the Pál-Vértesi-McKague-Mosca-Gisin method could not reproduce the experimental outcomes predicted by complex number quantum theory. This was a promising start, but it was not enough: similarly to what Bell achieved for classical theories, we needed to rule out the existence of *any* form of real quantum theory, no matter how clever or sophisticated, that could explain the results of quantum network experiments. For this, we needed to devise a concrete gedankenexperiment in a quantum network and show that the predictions of standard quantum theory were impossible to model with real quantum theory.

Initially we considered complicated networks involving six experimentalists and four sources. In the end, however, we settled for a simpler quantum experiment with three separate experimenters called Alice, Bob and Charlie and two independent particle sources. The first source sends out two particles of light (photons), one to Alice and one to Bob; the second one sends photons to Bob and Charlie. Next, Alice and Charlie choose a direction in which to measure the polarization of their particles, which can turn out to be "up" or "down." Meanwhile Bob measures his two particles. When we do this over and over again, we can build up a set of statistics showing how often the measurements correlate. These statistics depend on the directions Alice and Charlie choose.

Next, we needed to show that the observed statistics could not be predicted by any real quantum system. To do so, we relied on a powerful concept known as self-testing, which allows a scientist to certify both a measurement device and the system it's measuring at once. What does that mean? Think of a measurement apparatus—for instance, a weight scale. To guarantee that it's accurate, you need to test it with a mass of a certified weight. But how to certify this mass? You must use another scale, which itself needs to be certified, and so on. In classical physics, this process has no end. Astonishingly, in quantum theory, it's possible to certify both a measured system and a measurement device simultaneously, as if the scale and the test mass were checking each other's calibration.

With self-testing in mind, our impossibility proof worked as follows. We conceived of an experiment in which, for any of Bob's outcomes, Alice and Charlie's measurement statistics self-tested their shared quantum state. In other words, the statistics of one confirmed the quantum nature of the other, and vice versa. We found that the only description of the devices that was compatible with real quantum theory had to be precisely the Pál-Vértesi-McKague-Mosca-Gisin version, which we already knew didn't work for a quantum network. Hence, we arrived at the contradiction we were hoping for: real quantum theory could be falsified.

We also found that as long as any real-world measurement statistics observed by Alice, Bob and Charlie were close enough to those of our ideal gedankenexperiment, they could not be reproduced by real quantum systems. The logic was very similar to Bell's theorem: we ended up deriving a Bell's inequality for real quantum theory and proving that it could be violated by complex quantum theory, even in the presence of noise and imperfections. That allowance for noise is what makes our result testable in practice. No experimentalists ever achieve total control of their lab; the best they can hope for is to prepare quantum states that are approximately what they were aiming for and to make approximately the measurements they intended, which will allow them to generate approximately the same measurement statistics that were predicted. The good news is that within our proof, the experimental precision required to falsify real quantum theory, though demanding, was within reach of current technologies. When we announced our results, we hoped it was just a matter of time before someone, somewhere, would realize our vision.

It happened quickly. Just two months after we made our discovery public, an experimental group in Shanghai reported implementing our gedankenexperiment with superconducting qubits—computer bits made of quantum particles. Around the same time, a group in Shenzhen also contacted us to discuss carrying out our gedankenexperiment with optical systems. Months later we read about yet another optical version of the experiment, also conducted in Shanghai. In each case, the experimenters observed correlations between the measurements that real quantum theory could not account for. Although there are still a few experimental loopholes to take care of, taken together these three experiments make the real quantum hypothesis very difficult to sustain.

THE QUANTUM FUTURE

WE NOW KNOW neither classical nor real quantum theory can explain certain phenomena, so what comes next? If future versions of quantum theory are proposed as alternatives to the standard theory, we could use a similar technique to try to exclude them as well. Could we go one step further and falsify standard quantum theory itself?

If we did, we would be left with no theory for the microscopic world given that we currently lack an alternative. But physicists are not convinced that standard quantum theory is true. One reason is that it seems to conflict with one of our other theories, general relativity, used to describe gravity. Scientists are seeking a new, deeper theory that could reconcile these two and perhaps replace standard quantum theory. If we could ever falsify quantum theory, we might be able to point the way toward that deeper theory.

In parallel, some researchers are trying to prove that no theory other than quantum will do. One of our co-authors, Mirjam Weilenmann, in collaboration with Roger Colbeck, has argued that it may be possible to discard all alternative physical theories through suitable Bell-like experiments. If this were true, then those experiments would show that quantum mechanics is indeed the only physical theory compatible with experimental observations. The possibility makes us shiver: Can we really hope to demonstrate that quantum theory is so special? SA

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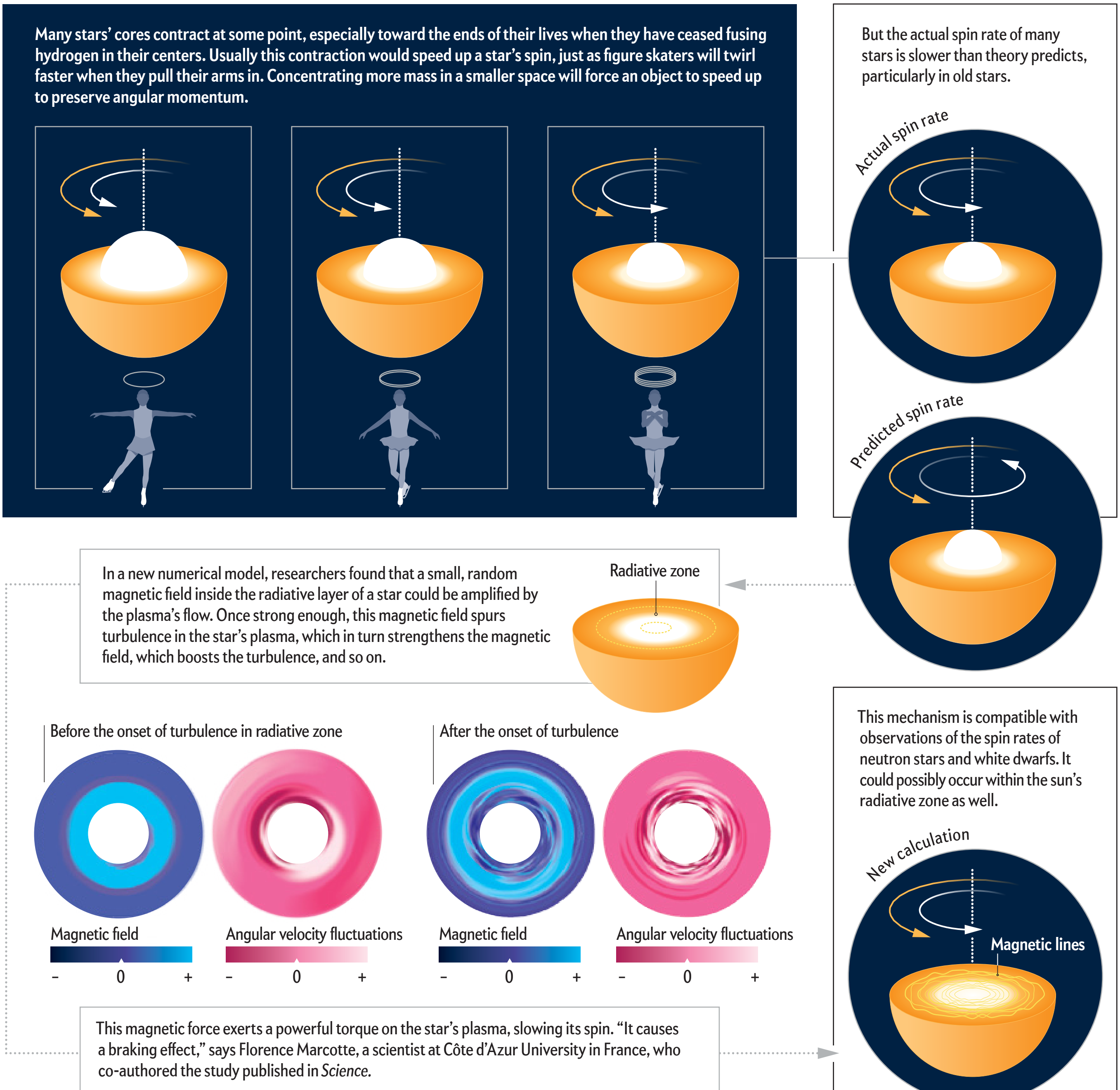
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Star Spin Mystery

Scientists wondered why the insides of stars are spinning so slowly

Text by Clara Moskowitz | Graphic by Lucy Reading-Ikkanda

Astronomers can measure how fast stars spin by observing “starquakes”—seismic tremors that are the equivalent of earthquakes on our planet. Yet these observations have posed a puzzle because many stars seem to be spinning slower than they should be. In a new study, researchers modeled how a magnetic field could grow in the internal layers of a star, dragging its rotation down.



Source: “Spin-Down by Dynamo Action in Simulated Radiative Stellar Layers,” by Ludovic Petitdemange, Florence Marcotte and Christophe Gissinger, in *Science*, Vol. 379; January 20, 2023 (*reference*)

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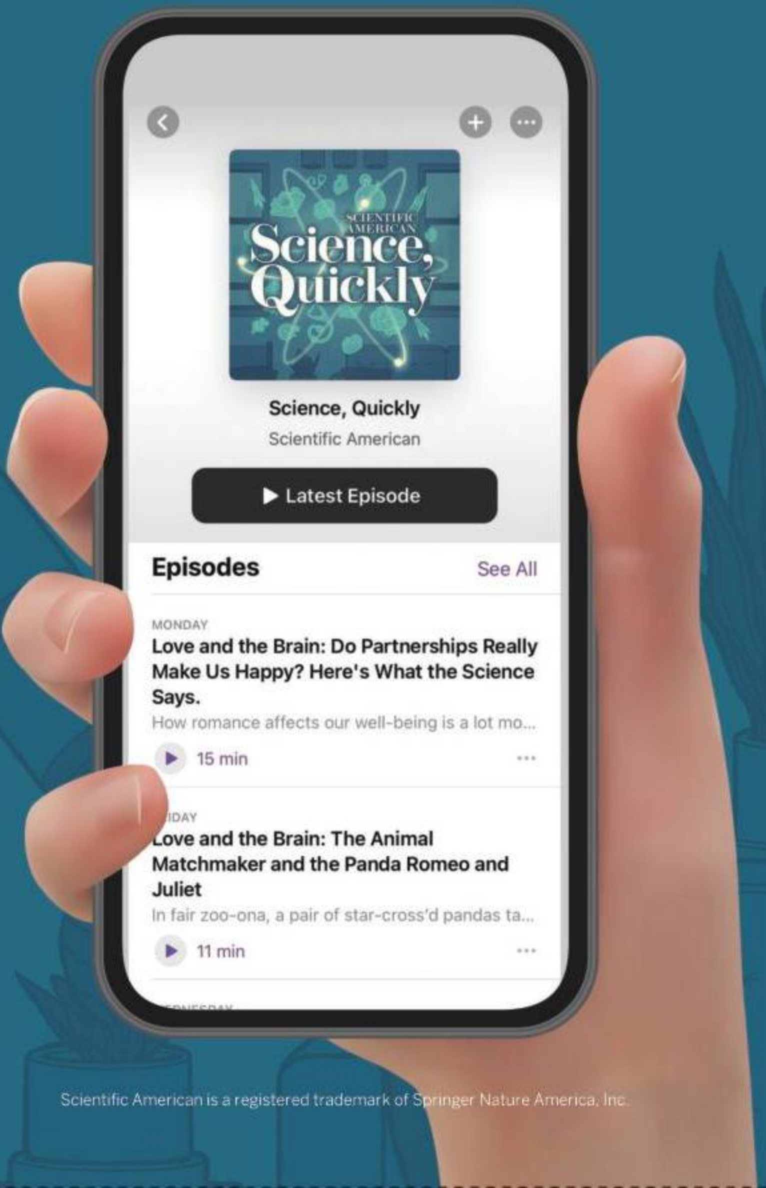
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